CHAPTER 3

SPECIAL AMPLIFIERS

LEARNING OBJECTIVES

Upon completion of this chapter, you will be able to:

1. Describe the basic operation of a differential amplifier.

2. Describe the operation of a differential amplifier under the following conditions:

    a. Single Input, Single Output

    b. Single input, differential output

    c. Differential input, differential output

3. List the characteristics of an operational amplifier.

4. Identify the symbol for an operational amplifier.

5. Label the blocks on a block diagram of an operational amplifier.

6. Describe the operation of an operational amplifier with inverting and noninverting configurations.

7. Describe the bandwidth of a typical operational amplifier and methods to modify the bandwidth.

8. Identify the following applications of operational amplifiers:

    a. Adder

    b. Subtractor

9. State the common usage for a magnetic amplifier.

10. Describe the basic operation of a magnetic amplifier.

11. Describe various methods of changing inductance.

12. Identify the purpose of components in a simple magnetic amplifier.

INTRODUCTION

If you were to make a quick review of the subjects discussed in this module up to this point, you would see that you have been given a considerable amount of information about amplifiers. You have been shown what amplification is and how the different classes of amplifiers affect amplification. You also have been shown that many factors must be considered when working with amplifiers, such as

impedance, feedback, frequency response, and coupling. With all this information behind you, you might ask yourself "what more can there be to know about amplifiers?"

There is a great deal more to learn about amplifiers. Even after you finish this chapter you will have only "scratched the surface" of the study of amplifiers. But, you will have prepared yourself for the remainder of the *NEETS*. This, in turn, should prepare you for further study and, perhaps, a career in electronics.

As in chapter 2, the circuits shown in this chapter are intended to present particular concepts to you. Therefore, the circuits may be incomplete or not practical for use in an actual piece of electronic equipment. You should keep in mind the fact that this text is intended to teach certain facts about amplifiers, and in order to simplify the illustrations used, complete operational circuits are not always shown.

In this chapter three types of special amplifiers are discussed. These are: DIFFERENTIAL AMPLIFIERS, OPERATIONAL AMPLIFIERS, and MAGNETIC AMPLIFIERS. These are called special amplifiers because they are used only in certain types of equipment.

The names of each of these special amplifiers describe the operation of the amplifier, NOT what is amplified. For example, a magnetic amplifier does not amplify magnetism but uses magnetic effects to produce amplification of an electronic signal.

A differential amplifier is an amplifier that can have two input signals and/or two output signals. This amplifier can amplify the difference between two input signals. A differential amplifier will also "cancel out" common signals at the two inputs.

One of the more interesting aspects of an operational amplifier is that it can be used to perform mathematical operations electronically. Properly connected, an operational amplifier can add, subtract, multiply, divide, and even perform the calculus operations of integration and differentiation. These amplifiers were originally used in a type of computer known as the "analog computer" but are now used in many electronic applications.

The magnetic amplifier uses a device called a "saturable core reactor" to control an a.c.output signal. The primary use of magnetic amplifiers is in power control systems.

These brief descriptions of the three special amplifiers are intended to provide you with a general idea of what these amplifiers are and how they can be used. The remaining sections of this chapter will provide you with more detailed information on these special amplifiers.

DIFFERENTIAL AMPLIFIERS

A differential amplifier has two possible inputs and two possible outputs. This arrangement means that the differential amplifier can be used in a variety of ways. Before examining the three basic configurations that are possible with a differential amplifier, you need to be familiar with the basic circuitry of a differential amplifier.

BASIC DIFFERENTIAL AMPLIFIER CIRCUIT

Before you are shown the operation of a differential amplifier, you will be shown how a simpler circuit works. This simpler circuit, known as the DIFFERENCE AMPLIFIER, has one thing in common

with the differential amplifier: It operates on the difference between two inputs. However, the difference amplifier has only one output while the differential amplifier can have two outputs.

By now, you should be familiar with some amplifier circuits, which should give you an idea of what a difference amplifier is like. In *NEETS, Module 7*, you were shown the basic configurations for transistor amplifiers. Figure 3-1 shows two of these configurations: the common emitter and the common base.

In view (A) of figure 3-1 a common-emitter amplifier is shown. The output signal is an amplified version of the input signal and is 180 degrees out of phase with the input signal. View (B) is a common-base amplifier. In this circuit the output signal is an amplified version of the input signal and is in phase with the input signal. In both of these circuits, the output signal is controlled by the base-to-emitter bias. As this bias changes (because of the input signal) the current through the transistor changes. This causes the output signal developed across the collector load (R2) to change. None of this information is new, it is just a review of what you have already been shown regarding transistor amplifiers.
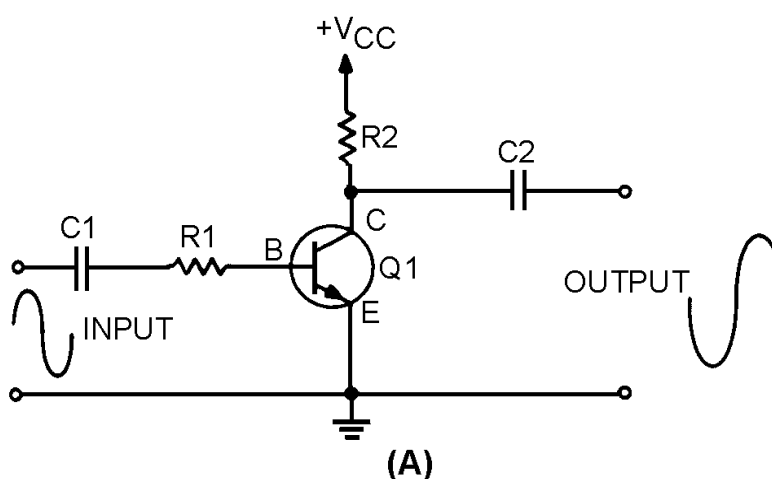

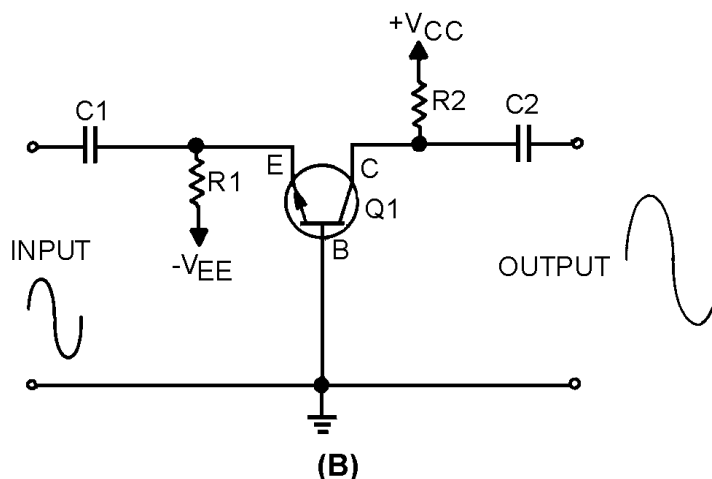**Figure 3-1A.—Common-emitter and common-base amplifiers.**

Figure 3-1B.—Common-emitter and common-base amplifiers.

NOTE: Bias arrangements for the following explanations will be termed base-to-emitter. In other publications you will see the term emitter-to-base used to describe the same bias arrangement.

THE TWO-INPUT, SINGLE-OUTPUT, DIFFERENCE AMPLIFIER

If you combine the common-base and common-emitter configurations into a single transistor amplifier, you will have a circuit like the one shown in figure 3-2. This circuit is the two-input, single-output, difference amplifier.
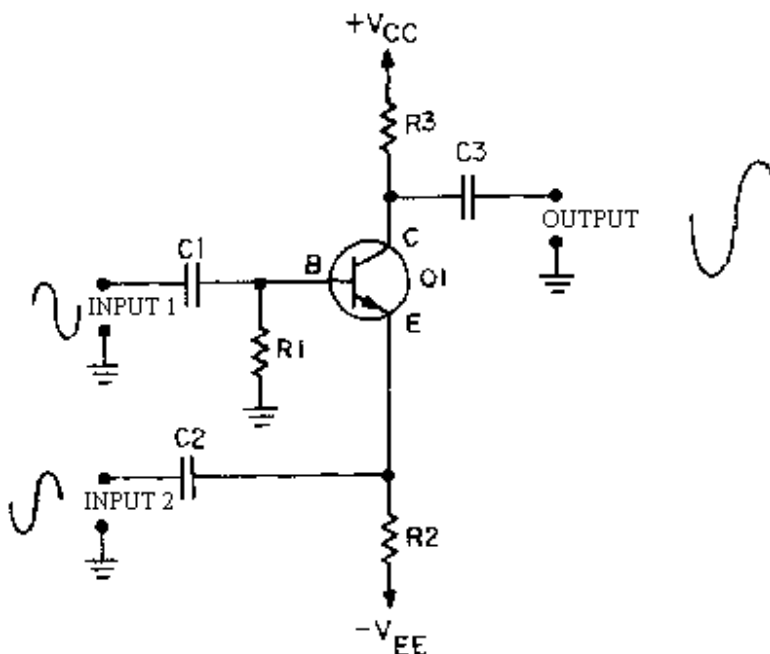

Figure 3-2.—Two-input, single-output, difference amplifier.

In figure 3-2, the transistor has two inputs (the emitter and the base) and one output (the collector). Remember, the current through the transistor (and therefore the output signal) is controlled by the base-to-emitter bias. In the circuit shown in figure 3-2, the combination of the two input signals controls the output signal. In fact, the DIFFERENCE BETWEEN THE INPUT SIGNALS determines the base-to-emitter bias.

For the purpose of examining the operation of the circuit shown in figure 3-2, assume that the circuit has a gain of -10. This means that for each 1-volt change in the base-to-emitter bias, there would be a 10-volt change in the output signal. Assume, also, that the input signals will peak at 1-volt levels (+1 volt for the positive peak and -1 volt for the negative peak). The secret to understanding this circuit (or any transistor amplifier circuit) is to realize that the collector current is controlled by the base-to-emitter bias. In other words, in this circuit the output signal (the voltage developed across R3) is determined by the difference between the voltage on the base and the voltage on the emitter.

Figure 3-3 shows this two-input, single-output amplifier with input signals that are equal in amplitude and 180 degrees out of phase. Input number one has a positive alternation when input number two has a negative alternation and vice versa.
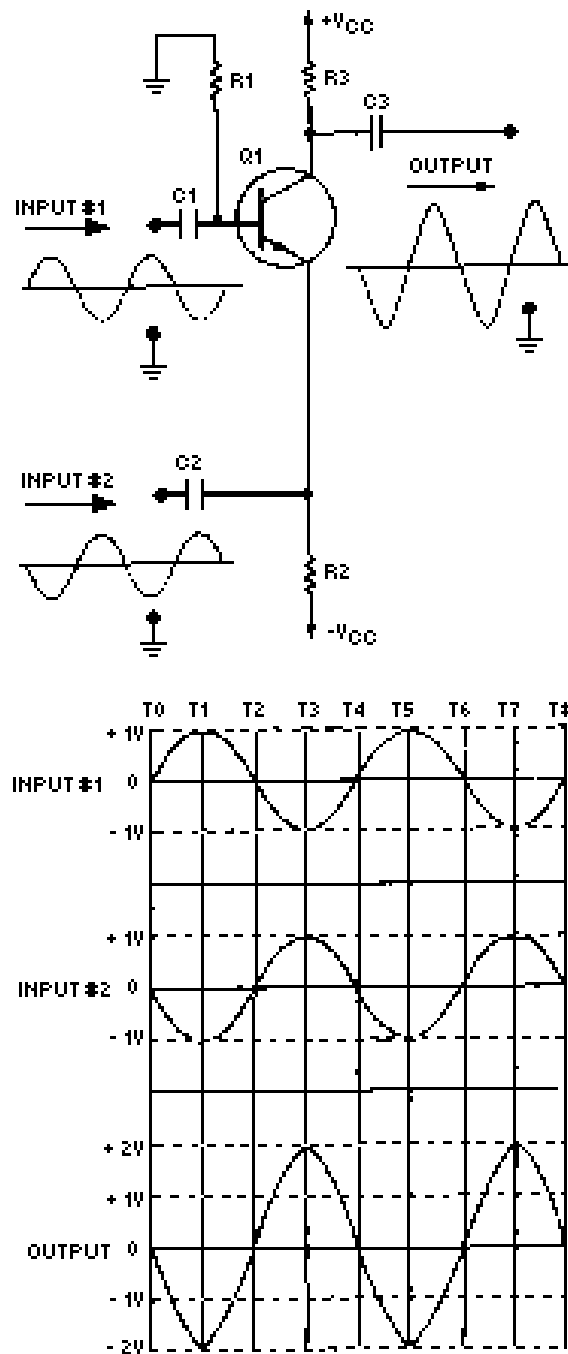
Figure 3-3.—Input signals 180° out of phase.

The circuit and the input and output signals are shown at the top of the figure. The lower portion of the figure is a comparison of the input signals and the output signal. Notice the vertical lines marked "T0" through "T8." These represent "time zero" through "time eight." In other words, these lines provide a way to examine the two input signals and the output signal at various instants of time.

In figure 3-3 at time zero (T0) both input signals are at 0 volts. The output signal is also at 0 volts. Between time zero (T0) and time one (T1), input signal number one goes positive and input signal number two goes negative. Each of these voltage changes causes an increase in the base-to-emitter bias which causes current through Q1 to increase. Increased current through Q1 results in a greater voltage drop across the collector load (R3) which causes the output signal to go negative.

By time one (T1), input signal number one has reached +1 volt and input signal number two has reached −1 volt. This is an overall increase in base-to-emitter bias of 2 volts. Since the gain of the circuit is −10, the output signal has decreased by 20 volts. As you can see, the output signal has been determined by the <u>difference between the two input signals</u>. In fact, the base-to-emitter bias can be found by subtracting the value of input signal number two from the value of input signal number one.

Mathematically:

Bias = (input signal #1) - (input signal #2)
Bias = (+1V) - (-1V)
Bias = +1V + 1V
Bias = +2V

Between time one (T1) and time two (T2), input signal number one goes from +1 volt to 0 volts and input signal number two goes from −1 volt to 0 volts. At time two (T2) both input signals are at 0 volts and the base-to-emitter bias has returned to 0 volts. The output signal is also 0 volts.

Mathematically:

Bias = (input signal #1) - (input signal #2)
Bias = (0V) - (0V)
Bias = 0V

Between time two (T2) and time three (T3), input signal number one goes negative and input signal number two goes positive. At time three (T3), the value of the base-to-emitter bias is −2 volts.

Mathematically:

Bias = (input signal #1) - (input signal #2)
Bias = (-1V) - (+1V)
Bias = (-1V) + (-1V)
Bias = -2V

This causes the output signal to be +20 volts at time three (T3).

Between time three (T3) and time four (T4), input signal #1 goes from −1 volt to 0 volts and input signal #2 goes from +1 volt to 0 volts. At time four (T4) both input signals are 0 volts, the bias is 0 volts, and the output is 0 volts.

During time four (T4) through time eight (T8), the circuit repeats the sequence of events that took place from time zero (T0) through time four (T4).

You can see that when the input signals are equal in amplitude and 180 degrees out of phase, the output signal is twice as large (40 volts peak to peak) as it would be from either input signal alone (if the other input signal were held at 0 volts).

Figure 3-4 shows the two-input, single-output, difference amplifier with two input signals that are equal in amplitude and in phase.
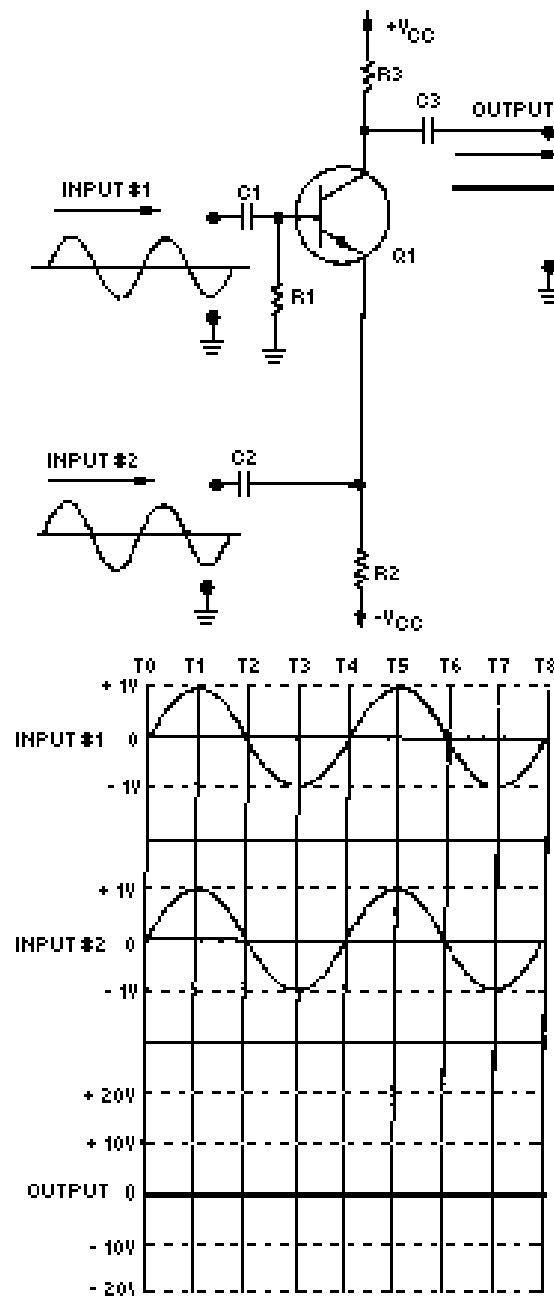

Figure 3-4.—Input signals in phase.

Notice, that the output signal remains at 0 volts for the entire time (T0 - T8). Since the two input signals are equal in amplitude and in phase, the difference between them (the base-to-emitter bias) is always 0 volts. This causes a 0-volt output signal.

If you compute the bias at any time period (T0 - T8), you will see that the output of the circuit remains at a constant zero.

For example:

$$\text{Bias} = (\text{input signal \#1}) - (\text{input signal \#2})$$
$$\text{T1 Bias} = (+1V) - (+1V) = 0$$
$$\text{and so forth}$$

From the above example, you can see that when the input signals are equal in amplitude and in phase, there is no output from the difference amplifier because there is no difference between the two inputs. You also know that when the input signals are equal in amplitude but 180 degrees out of phase, the output looks just like the input except for amplitude and a 180-degree phase reversal with respect to input signal number one. What happens if the input signals are equal in amplitude but different in phase by something other than 180 degrees? This would mean that sometimes one signal would be going negative while the other would be going positive; sometimes both signals would be going positive; and sometimes both signals would be going negative. Would the output signal still look like the input signals? The answer is "no," because figure 3-5 shows a difference amplifier with two input signals that are equal in amplitude but 90 degrees out of phase. From the figure you can see that at time zero (T0) input number one is at 0 volts and input number two is at -1 volt. The base-to-emitter bias is found to be +1 volt.
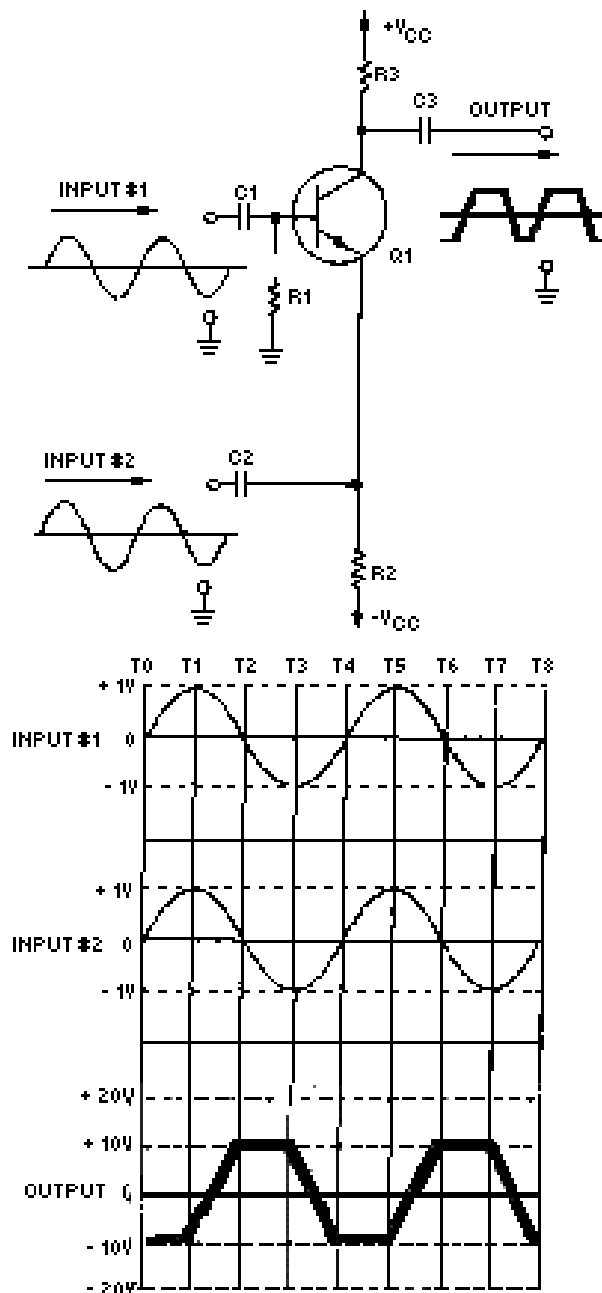
Figure 3-5.—Input signals 90º out of phase.

This +1-volt bias signal causes the output signal to be −10 volts at time zero (T0). Between time zero (T0) and time one (T1), both input signals go positive. The difference between the input signals stays constant. The effect of this is to keep the bias at +1 volt for the entire time between T0 and T1. This, in turn, keeps the output signal at -10 volts.

Between time one (T1) and time two (T2), input signal number one goes in a negative direction but input signal number two continues to go positive. Now the difference between the input signals decreases

3-9

rapidly from +1 volt. Halfway between T1 and T2 (the dotted vertical line), input signal number one and input signal number two are equal in amplitude. The difference between the input signals is 0 volts and this causes the output signal to be 0 volts. From this point to T2 the difference between the input signals is a negative value. At T2:

$$Bias = (input\ signal\ \#1) - (input\ signal\ \#2)$$
$$Bias = (0V) - (+1V)$$
$$Bias = +1V$$

From time two (T2) to time three (T3), input signal number one goes negative and input signal number two goes to zero. The difference between them stays constant at -1 volt. Therefore, the output signal stays at a +10-volt level for the entire time period from T2 to T3. At T3 the bias condition will be:

$$Bias = (input\ signal\ \#1) - (input\ signal\ \#2)$$
$$Bias = (0V) - (-1V)$$
$$Bias = +1V$$

Between T3 and T4 input signal number one goes to zero while input signal number two goes negative. This, again, causes a rapid change in the difference between the input signals. Halfway between T3 and T4 (the dotted vertical line) the two input signals are equal in amplitude; therefore, the difference between the input signals is 0 volts, and the output signal becomes 0 volts. From that point to T4, the difference between the input signals becomes a positive voltage. At T4:

$$Bias = (input\ signal\ \#1) - (input\ signal\ \#2)$$
$$Bias = (0V) - (-1V)$$
$$Bias = +1V$$

(The sequence of events from T4 to T8 are the same as those of T0 to T4.)

As you have seen, this amplifier amplifies the difference between two input signals. But this is NOT a differential amplifier. A differential amplifier has two inputs and two outputs. The circuit you have just been shown has only one output. Well then, how does a differential amplifier schematic look?

TYPICAL DIFFERENTIAL AMPLIFIER CIRCUIT

Figure 3-6 is the schematic diagram of a typical differential amplifier. Notice that there are two inputs and two outputs. This circuit requires two transistors to provide the two inputs and two outputs. If you look at one input and the transistor with which it is associated, you will see that each transistor is a common-emitter amplifier for that input (input one and Q1; input two and Q2). R1 develops the signal at input one for Q1, and R5 develops the signal at input two for Q2. R3 is the emitter resistor for both Q1 and Q2. Notice that R3 is NOT bypassed. This means that when a signal at input one affects the current through Q1, that signal is developed by R3. (The current through Q1 must flow through R3; as this current changes, the voltage developed across R3 changes.) When a signal is developed by R3, it is applied to the emitter of Q2. In the same way, signals at input two affect the current of Q2, are developed by R3, and are felt on the emitter of Q1. R2 develops the signal for output one, and R4 develops the signal for output two.
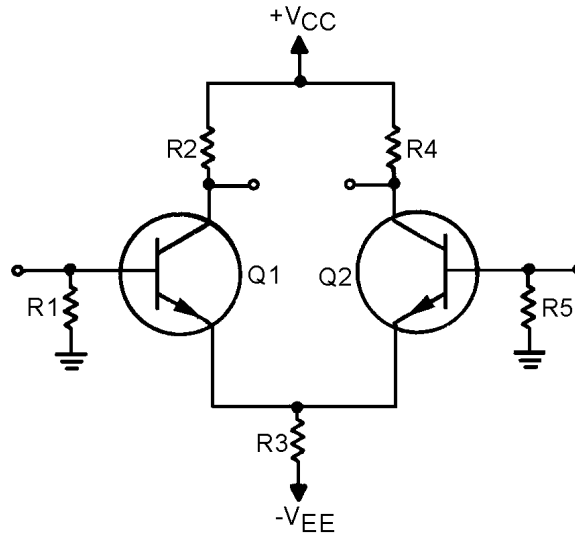
Figure 3-6.—Differential amplifier.

Even though this circuit is designed to have two inputs and two outputs, it is not necessary to use both inputs and both outputs. (Remember, a differential amplifier was defined as having two <u>possible</u> inputs and two <u>possible</u> outputs.) A differential amplifier can be connected as a single-input, single-output device; a single-input, differential-output device; or a differential-input, differential-output device.

Q-1.   How many inputs and outputs are possible with a differential amplifier?

Q-2.   What two transistor amplifier configurations are combined in the single-transistor, two-input, single-output difference amplifier?

Q-3.   If the two input signals of a difference amplifier are in phase and equal in amplitude, what will the output signal be?

Q-4.   If the two input signals to a difference amplifier are equal in amplitude and 180 degrees out of phase, what will the output signal be?

Q-5.   If only one input signal is used with a difference amplifier, what will the output signal be?

Q-6.   If the two input signals to a difference amplifier are equal in amplitude but neither in phase nor 180 degrees out of phase, what will the output signal be?

SINGLE-INPUT, SINGLE-OUTPUT, DIFFERENTIAL AMPLIFIER

Figure 3-7 shows a differential amplifier with one input (the base of Q1) and one output (the collector of Q2). The second input (the base of Q2) is grounded and the second output (the collector of Q1) is not used.
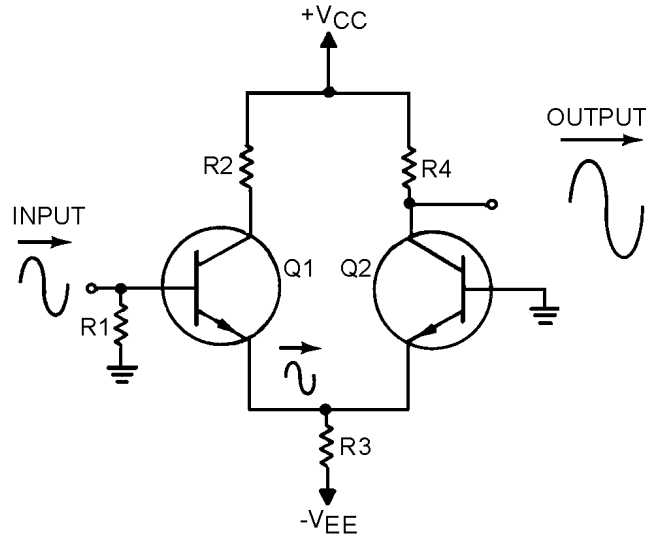
Figure 3-7.—Single-input, single-output differential amplifier.

When the input signal developed by R1 goes positive, the current through Q1 increases. This increased current causes a positive-going signal at the top of R3. This signal is felt on the emitter of Q2. Since the base of Q2 is grounded, the current through Q2 decreases with a positive-going signal on the emitter. This decreased current causes less voltage drop across R4. Therefore, the voltage at the bottom of R4 increases and a positive-going signal is felt at the output.

When the input signal developed by R1 goes negative, the current through Q1 decreases. This decreased current causes a negative-going signal at the top of R3. This signal is felt on the emitter of Q2. When the emitter of Q2 goes negative, the current through Q2 increases. This increased current causes more of a voltage drop across R4. Therefore, the voltage at the bottom of R4 decreases and a negative-going signal is felt at the output.

This single-input, single-output, differential amplifier is very similar to a single-transistor amplifier as far as input and output signals are concerned. This use of a differential amplifier does provide amplification of a.c. or d.c. signals but does not take full advantage of the characteristics of a differential amplifier.

SINGLE-INPUT, DIFFERENTIAL-OUTPUT, DIFFERENTIAL AMPLIFIER

In chapter one of this module you were shown several phase splitters. You should remember that a phase splitter provides two outputs from a single input. These two outputs are 180 degrees out of phase with each other. The single-input, differential-output, differential amplifier will do the same thing.

Figure 3-8 shows a differential amplifier with one input (the base of Q1) and two outputs (the collectors of Q1 and Q2). One output is in phase with the input signal, and the other output is 180 degrees out of phase with the input signal. The outputs are differential outputs.
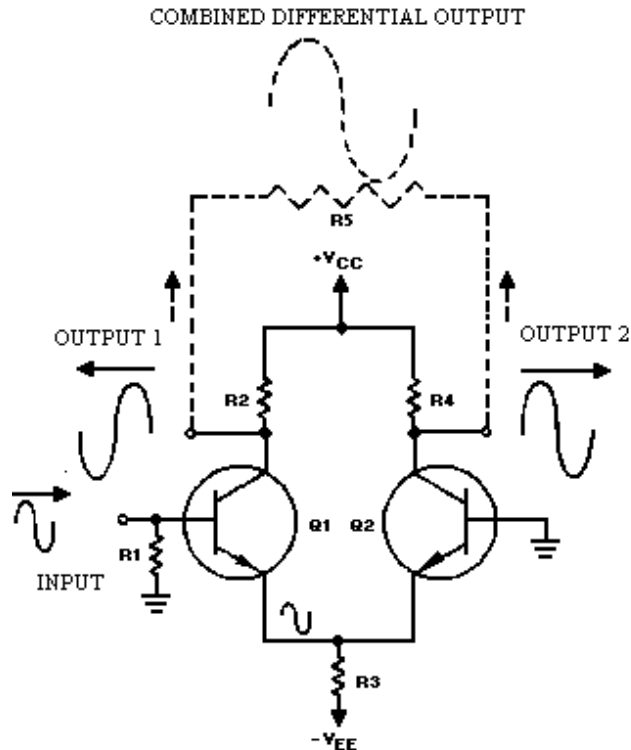
Figure 3-8.—Single-input, differential-output differential amplifier.

This circuit's operation is the same as for the single-input, single-output differential amplifier just described. However, another output is obtained from the bottom of R2. As the input signal goes positive, thus causing increased current through Q1, R2 has a greater voltage drop. The output signal at the bottom of R2 therefore is negative going. A negative-going input signal will decrease current and reverse the polarities of both output signals.

Now you see how a differential amplifier can produce two amplified, differential output signals from a single-input signal. One further point of interest about this configuration is that if a combined output signal is taken between outputs number one and two, this single output will be twice the amplitude of the individual outputs. In other words, you can double the gain of the differential amplifier (single output) by taking the output signal between the two output terminals. This single-output signal will be in phase with the input signal. This is shown by the phantom signal above R5 (the phantom resistor connected between outputs number one and two would be used to develop this signal).

DIFFERENTIAL-INPUT, DIFFERENTIAL-OUTPUT, DIFFERENTIAL AMPLIFIER

When a differential amplifier is connected with a differential input and a differential output, the full potential of the circuit is used. Figure 3-9 shows a differential amplifier with this type of configuration (differential-input, differential-output).
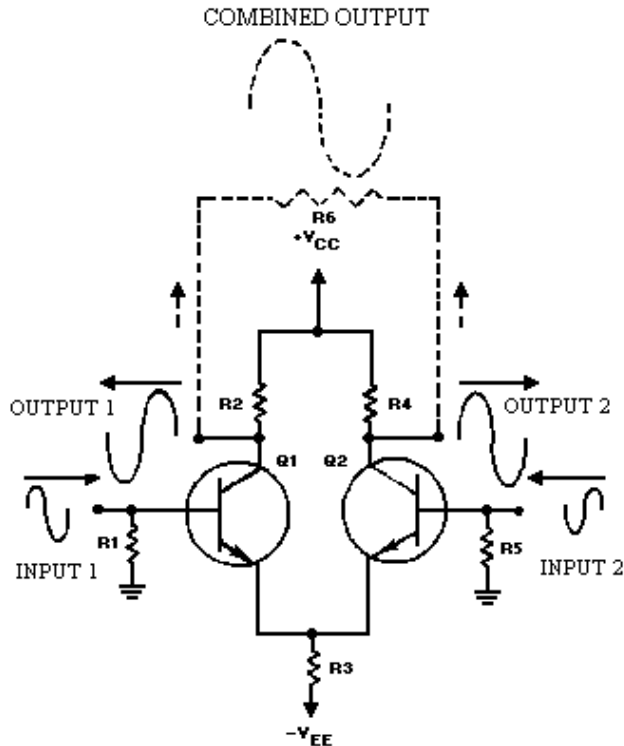
Figure 3-9.—Differential-input, differential-output differential amplifier.

Normally, this configuration uses two input signals that are 180 degrees out of phase. This causes the difference (differential) signal to be twice as large as either input alone. (This is just like the two-input, single-output difference amplifier with input signals that are 180 degrees out of phase.)

Output number one is a signal that is in phase with input number two, and output number two is a signal that is in phase with input number one. The amplitude of each output signal is the input signal multiplied by the gain of the amplifier. With 180-degree-out-of-phase input signals, each output signal is greater in amplitude than either input signal by a factor of the gain of the amplifier.

When an output signal is taken between the two output terminals of the amplifier (as shown by the phantom connections, resistor, and signal), the combined output signal is twice as great in amplitude as either signal at output number one or output number two. (This is because output number one and output number two are 180 degrees out of phase with each other.) When the input signals are 180 degrees out of phase, the amplitude of the combined output signal is equal to the amplitude of one input signal multiplied by two times the gain of the amplifier.

When the input signals are not 180 degrees out of phase, the combined output signal taken across output one and output two is similar to the output that you were shown for the two-input, single-output, difference amplifier. The differential amplifier can have two outputs (180 degrees out of phase with each other), or the outputs can be combined as shown in figure 3-9.

In answering Q7 through Q9 use the following information: All input signals are sine waves with a peak-to-peak amplitude of 10 millivolts. The gain of the differential amplifier is 10.

Q-7.   If the differential amplifier is configured with a single input and a single output, what will the peak-to-peak amplitude of the output signal be?

Q-8.   *If the differential amplifier is configured with a single input and differential outputs, what will the output signals be?*

Q-9.   *If the single-input, differential-output, differential amplifier has an output signal taken between the two output terminals, what will the peak-to-peak amplitude of this combined output be?*

In answering Q10 through Q14 use the following information: A differential amplifier is configured with a differential input and a differential output. All input signals are sine waves with a peak-to-peak amplitude of 10 millivolts. The gain of the differential amplifier is 10.

Q-10.   *If the input signals are in phase, what will be the peak-to-peak amplitude of the output signals?*

Q-11.   *If the input signals are 180 degrees out of phase with each other, what will be the peak-to-peak amplitude of the output signals?*

Q-12.   *If the input signals are 180 degrees out of phase with each other, what will the phase relationship be between (a) the output signals and (b) the input and output signals?*

Q-13.   *If the input signals are 180 degrees out of phase with each other and a combined output is taken between the two output terminals, what will the amplitude of the combined output signal be?*

Q-14.   *If the input signals are 90 degrees out of phase with each other and a combined output is taken between the two output terminals, (a) what will the peak-to-peak amplitude of the combined output signal be, and (b) will the combined output signal be a sine wave?*

OPERATIONAL AMPLIFIERS

An OPERATIONAL AMPLIFIER (OP AMP) is an amplifier which is designed to be used with other circuit components to perform either computing functions (addition, subtraction) or some type of transfer operation, such as filtering. Operational amplifiers are usually high-gain amplifiers with the amount of gain determined by feedback.

Operational amplifiers have been in use for some time. They were originally developed for analog (non-digital) computers and used to perform mathematical functions. Operational amplifiers were not used in other devices very much because they were expensive and more complicated than other circuits.

Today many devices use operational amplifiers. Operational amplifiers are used as d.c. amplifiers, a.c. amplifiers, comparators, oscillators (which are covered in *NEETS, Module 9*), filter circuits, and many other applications. The reason for this widespread use of the operational amplifier is that it is a very versatile and efficient device. As an integrated circuit (chip) the operational amplifier has become an inexpensive and readily available "building block" for many devices. In fact, an operational amplifier in integrated circuit form is no more expensive than a good transistor.

CHARACTERISTICS OF AN OPERATIONAL AMPLIFIER

The schematic symbols for an operational amplifier are shown in figure 3-10. View (A) shows the power supply requirements while view (B) shows only the input and output terminals. An operational amplifier is a special type of high-gain, d.c. amplifier. To be classified as an operational amplifier, the circuit must have certain characteristics. The three most important characteristics of an operational amplifier are:

1. Very high gain

2. Very high input impedance
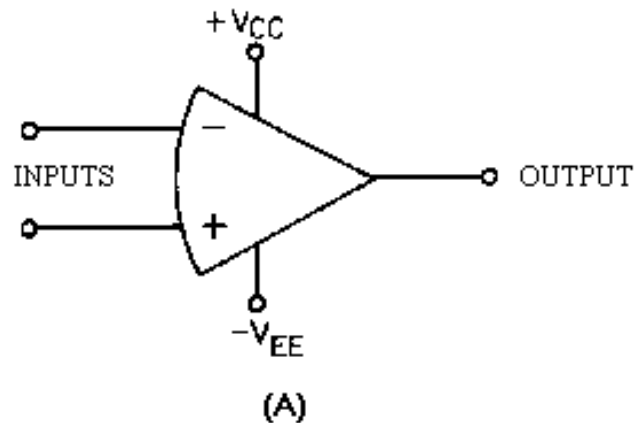
3. Very low output impedance

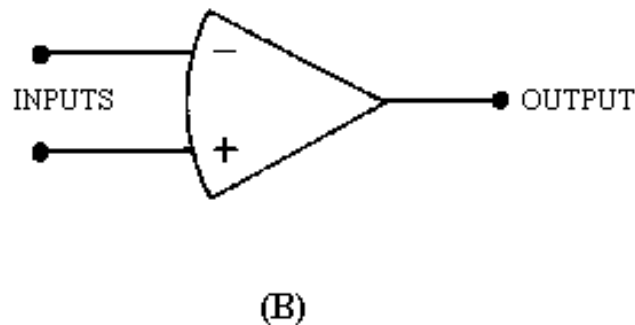Figure 3-10A.—Schematic symbols of an operational amplifier.

Figure 3-10B.—Schematic symbols of an operational amplifier.

Since no single amplifier stage can provide all these characteristics well enough to be considered an operational amplifier, various amplifier stages are connected together. The total circuit made up of these individual stages is called an operational amplifier. This circuit (the operational amplifier) can be made up of individual components (transistors, resistors, capacitors, etc.), but the most common form of the operational amplifier is an integrated circuit. The integrated circuit (chip) will contain the various stages of the operational amplifier and can be treated and used as if it were a single stage.

BLOCK DIAGRAM OF AN OPERATIONAL AMPLIFIER

Figure 3-11 is a block diagram of an operational amplifier. Notice that there are three stages within the operational amplifier.
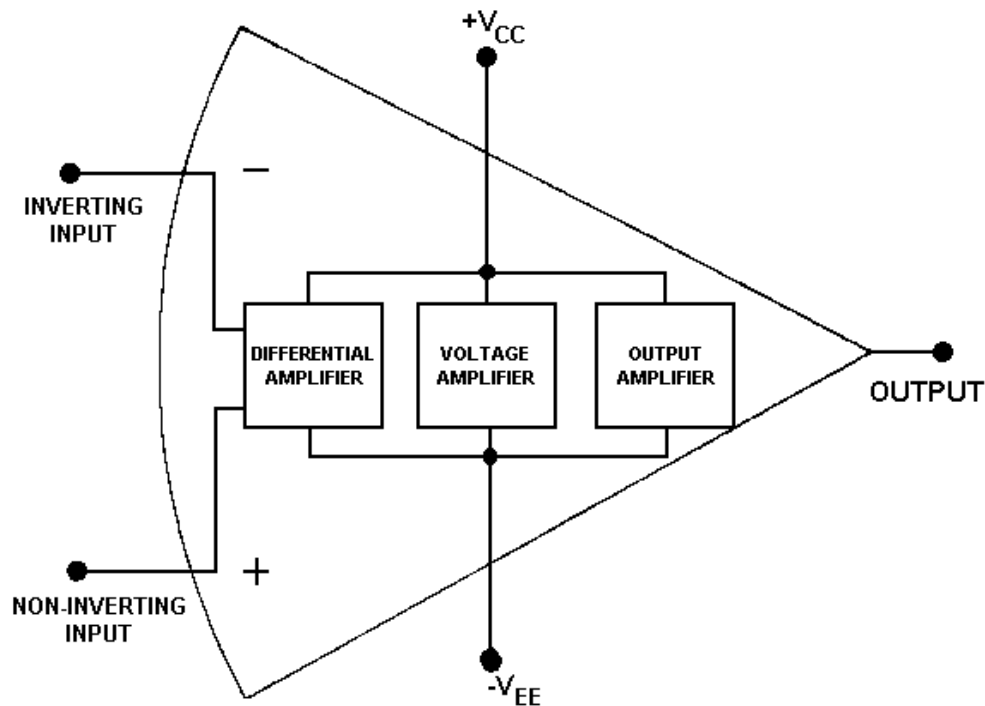
Figure 3-11.—Block diagram of an operational amplifier.

The input stage is a differential amplifier. The differential amplifier used as an input stage provides differential inputs and a frequency response down to d.c. Special techniques are used to provide the high input impedance necessary for the operational amplifier.

The second stage is a high-gain voltage amplifier. This stage may be made from several transistors to provide high gain. A typical operational amplifier could have a voltage gain of 200,000. Most of this gain comes from the voltage amplifier stage.

The final stage of the OP AMP is an output amplifier. The output amplifier provides low output impedance. The actual circuit used could be an emitter follower. The output stage should allow the operational amplifier to deliver several milliamperes to a load.

Notice that the operational amplifier has a positive power supply $(+V_{CC})$ and a negative power supply $(-V_{EE})$. This arrangement enables the operational amplifier to produce either a positive or a negative output.

The two input terminals are labeled "inverting input" (−) and "noninverting input" (+). The operational amplifier can be used with three different input conditions (modes). With differential inputs (first mode), both input terminals are used and two input signals which are 180 degrees out of phase with each other are used. This produces an output signal that is in phase with the signal on the noninverting input. If the noninverting input is grounded and a signal is applied to the inverting input (second mode), the output signal will be 180 degrees out of phase with the input signal (and one-half the amplitude of the first mode output). If the inverting input is grounded and a signal is applied to the noninverting input (third mode), the output signal will be in phase with the input signal (and one-half the amplitude of the first mode output).

Q-15. What are the three requirements for an operational amplifier?

Q-16. What is the most commonly used form of the operational amplifier?

Q-17. Draw the schematic symbol for an operational amplifier.

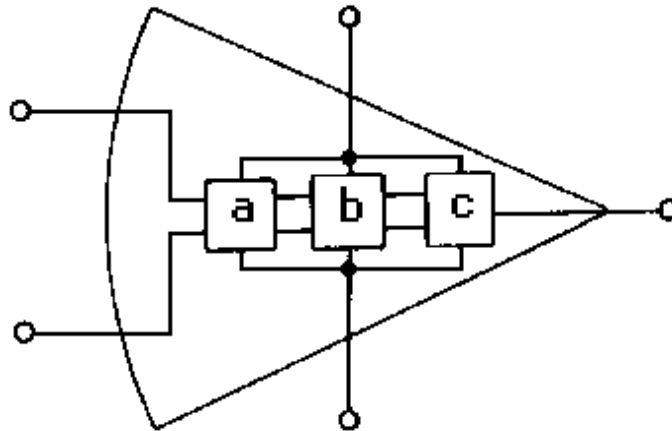*Q-18. Label the parts of the operational amplifier shown in figure 3-12.*

Figure 3-12.—Operational amplifier.

CLOSED-LOOP OPERATION OF AN OPERATIONAL AMPLIFIER

Operational amplifiers can have either a closed-loop operation or an open-loop operation. The operation (closed-loop or open-loop) is determined by whether or not feedback is used. Without feedback the operational amplifier has an open-loop operation. This open-loop operation is practical only when the operational amplifier is used as a comparator (a circuit which compares two input signals or compares an input signal to some fixed level of voltage). As an amplifier, the open-loop operation is not practical because the very high gain of the operational amplifier creates poor stability. (Noise and other unwanted signals are amplified so much in open-loop operation that the operational amplifier is usually not used in this way.) Therefore, most operational amplifiers are used with feedback (closed-loop operation).

Operational amplifiers are used with degenerative (or negative) feedback which reduces the gain of the operational amplifier but greatly increases the stability of the circuit. In the closed-loop configuration, the output signal is applied back to one of the input terminals. This feedback is always degenerative (negative). In other words, the feedback signal always opposes the effects of the original input signal. One result of degenerative feedback is that the inverting and noninverting inputs to the operational amplifier will be kept at the same potential.

Closed-loop circuits can be of the inverting configuration or noninverting configuration. Since the inverting configuration is used more often than the noninverting configuration, the inverting configuration will be shown first.

Inverting Configuration

Figure 3-13 shows an operational amplifier in a closed-loop, inverting configuration. Resistor R2 is used to feed part of the output signal back to the input of the operational amplifier.
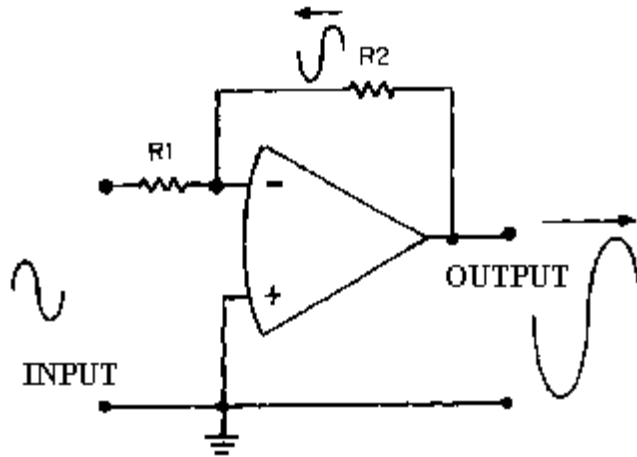
Figure 3-13.—Inverting configuration.

At this point it is important to keep in mind the difference between the entire circuit (or operational circuit) and the operational amplifier. The operational amplifier is represented by the triangle-like symbol while the operational circuit includes the resistors and any other components as well as the operational amplifier. In other words, the input to the circuit is shown in figure 3-13, but the signal at the inverting input of the operational amplifier is determined by the feedback signal as well as by the circuit input signal.

As you can see in figure 3-13, the output signal is 180 degrees out of phase with the input signal. The feedback signal is a portion of the output signal and, therefore, also 180 degrees out of phase with the input signal. Whenever the input signal goes positive, the output signal and the feedback signal go negative. The result of this is that the inverting input to the operational amplifier is always very close to 0 volts with this configuration. In fact, with the noninverting input grounded, the voltage at the inverting input to the operational amplifier is so small compared to other voltages in the circuit that it is considered to be VIRTUAL GROUND. (Remember, in a closed-loop operation the inverting and noninverting inputs are at the same potential.)

Virtual ground is a point in a circuit which is at ground potential (0 volts) but is NOT connected to ground. Figure 3-14, (view A) (view B) and (view C), shows an example of several circuits with points at virtual ground.
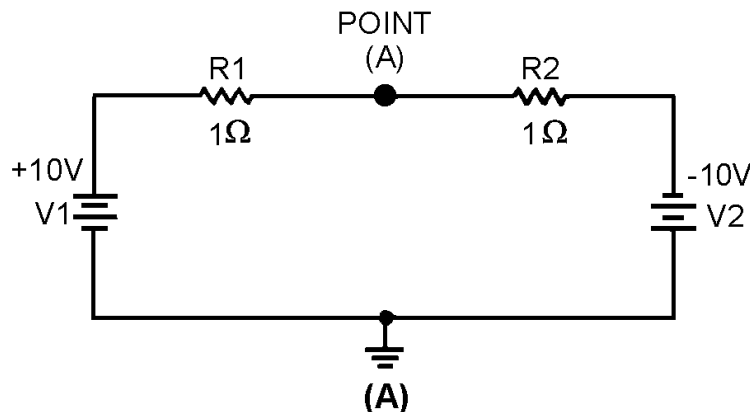

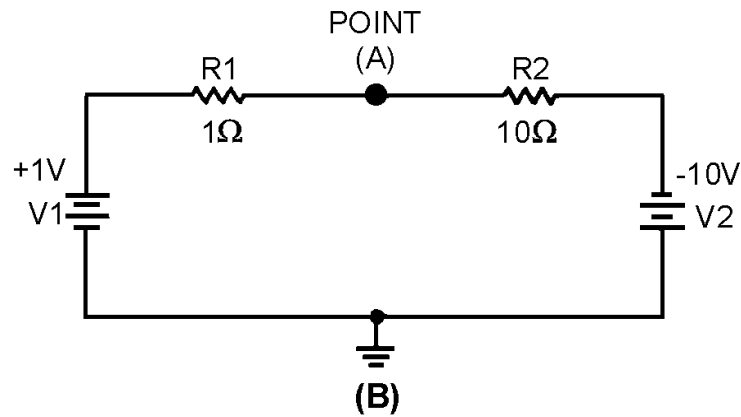**Figure 3-14A.—Virtual ground circuits.**

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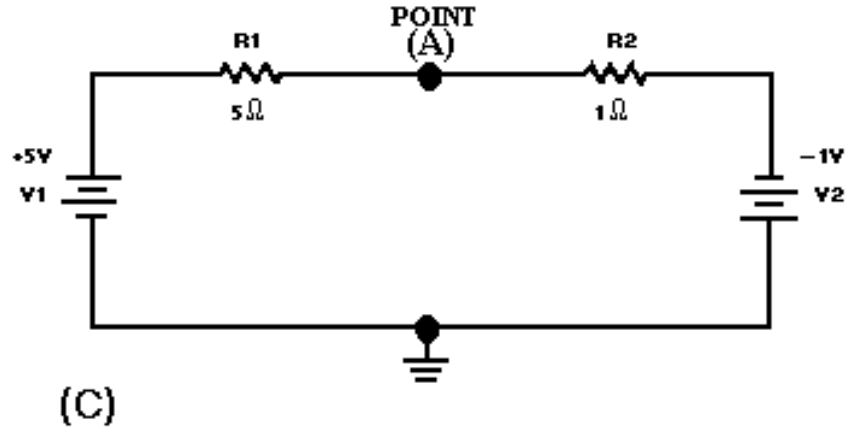**Figure 3-14B.—Virtual ground circuits.**

Figure 3-14C.—Virtual ground circuits.

In view (A), V1 (the left-hand battery) supplies +10 volts to the circuit while V2 (the right-hand battery) supplies -10 volts to the circuit. The total difference in potential in the circuit is 20 volts.

The total resistance of the circuit can be calculated:

$$R_T = R_1 + R_2$$
$$R_T = 1\Omega + 1\Omega$$
$$R_T = 2\Omega$$

Now that the total resistance is known, the circuit current can be calculated:

$$I_T = \frac{E_T}{R_T}$$

$$I_T = \frac{20V}{2\Omega}$$

$$I_T = 10A$$

The voltage drop across R1 can be computed:

$$E_{R1} = R_1 \times I_T$$
$$E_{R1} = 1\Omega \times 10A$$
$$E_{R1} = 10V$$

The voltage at point A would be equal to the voltage of V1 minus the voltage drop of R1.

Voltage at point A = V1 - E_{R1}
Voltage at point A = +10V - 10V
Voltage at point A = 0V

To check this result, compute the voltage drop across R2 and subtract this from the voltage at point A. The result should be the voltage of V2.

$E_{R2} = R_1 \times I_T$
$E_{R2} = 1\Omega \times 10A$
$E_{R2} = 10V$
V2 = (voltage at point A) - (E_{R2})
V2 = (0V) - (10V)
V2 = -10V

It is not necessary that the voltage supplies be equal to create a point of virtual ground. In view (B) V1 supplies +1 volt to the circuit while V2 supplies -10 volts. The total difference in potential is 11 volts. The total resistance of this circuit (R1 + R2) is 11 ohms. The total current (I_T) is 1 ampere. The voltage drop across R1 ($E_{R1} = R_1 \times I_T$) is 1 volt. The voltage drop across R2 ($E_{R2} = R2 \times I_T$) is 10 volts. The voltage at point A can be computed:

Voltage at point A = V1 - E_{R1}
Voltage at point A = (+1V) - (+1V)
Voltage at point A = 0V

So point A is at virtual ground in this circuit also. To check the results, compute the voltage at V2.

V2 = (voltage at point A) - E_{R1}
V2 = (0V) - (+10V)
V2 = -10V

You can compute the values for view (C) and prove that point A in that circuit is also at virtual ground.

The whole point is that the inverting input to the operational amplifier shown in figure 3-13 is at virtual ground since it is at 0 volts (for all practical purposes). Because the inverting input is at 0 volts, there will be no current (for all practical purposes) flowing into the operational amplifier from the connection point of R1 and R2.

Given these conditions, the characteristics of this circuit are determined almost entirely by the values of R1 and R2. Figure 3-15 should help show how the values of R1 and R2 determine the circuit characteristics.
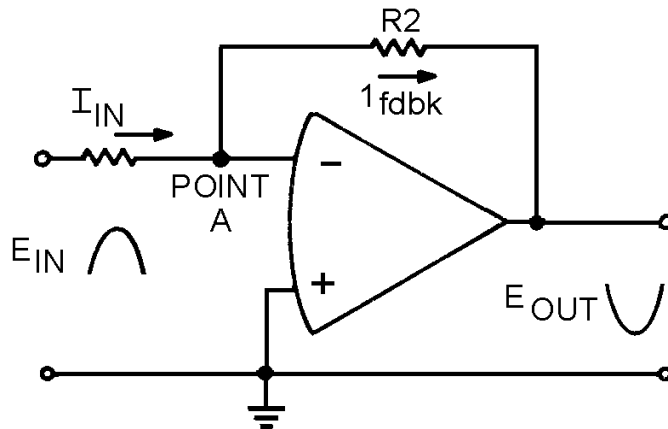
Figure 3-15.—Current flow in the operational circuit.

NOTE: It should be stressed at this point that for purpose of explanation the operational amplifier is a theoretically perfect amplifier. In actual practice we are dealing with less than perfect. In the practical operational amplifier there will be a slight input current with a resultant power loss. This small signal can be measured at the theoretical point of virtual ground. This does not indicate faulty operation.

The input signal causes current to flow through R1. (Only the positive half cycle of the input signal is shown and will be discussed.) Since the voltage at the inverting input of the operational amplifier is at 0 volts, the input current (I_{in}) is computed by:

$$I_{in} = \frac{E_{in}}{R_1}$$

The output signal (which is opposite in phase to the input signal) causes a feedback current (I_{fdbk}) to flow through R2. The left-hand side of R2 is at 0 volts (point A) and the right-hand side is at E_{out}. Therefore, the feedback current is computed by:

$$I_{fdbk} = \frac{-E_{out}}{R_2}$$

(The minus sign indicates that E_{out} is 180 degrees out of phase with E_{in} and should not be confused with output polarity.)

Since no current flows into or out of the inverting input of the operational amplifier, any current reaching point A from R1 must flow out of point A through R2. Therefore, the input current (I_{in}) and the feedback current (I_{fdbk}) must be equal. Now we can develop a mathematical relationship between the input and output signals and R1 and R2.

Mathematically:

$$I_{in} = I_{fdbk}$$

By substituition:

$$\frac{E_{in}}{R_1} = \frac{-E_{out}}{R_2}$$

If you multiply both sides of the equation by R1:

$$E_{in} = \frac{-(E_{out})(R1)}{R2}$$

If you divide both sides of the equation by E_{out}:

$$\frac{E_{in}}{E_{out}} = -\frac{R_1}{R_2}$$

By inverting both sides of the equation:

$$\frac{E_{in}}{E_{out}} = -\frac{R_2}{R_1}$$

You should recall that the voltage gain of a stage is defined as the output voltage divided by the input voltage:

$$\left(\frac{E_{out}}{E_{in}}\right)$$

Therefore, the voltage gain of the inverting configuration of the operational amplifier is expressed by the equation:

$$-\frac{R_1}{R_2}$$

(As stated earlier, the minus sign indicates that the output signal is 180 degrees out of phase with the input signal.)

Noninverting Configuration

Figure 3-16 shows a noninverting configuration using an operational amplifier. The input signal (E_{in}) is applied directly to the noninverting (+) input of the operational amplifier. Feedback is provided by

coupling part of the output signal (E_{out}) back to the inverting (-) input of the operational amplifier. R1 and R2 act as voltage divider that allows only a part of the output signal to be applied as feedback (E_{fdbk}).
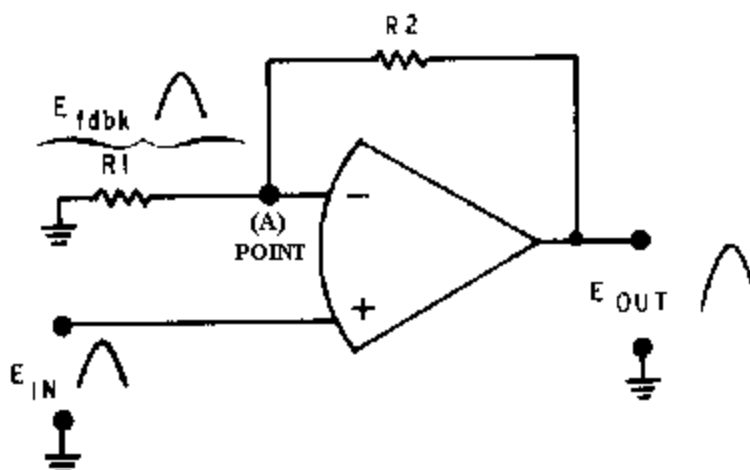

Figure 3-16.—Noninverting configuration.

Notice that the input signal, output signal, and feedback signal are all in phase. (Only the positive alternation of the signal is shown.) It may appear as if the feedback is regenerative (positive) because the feedback and input signals are in phase. The feedback is, in reality, degenerative (negative) because the input signals is applied to the noninverting input and the feedback signal is applied to the inverting input, (Remember, that the operational amplifier will react to the difference between the two inputs.)

Just as in the inverting configuration, the feedback signal is equal to the input signal (for all practical purposes). This time, however, the feedback signal is in phase with the input signal.

Therefore:

$$E_{in} = E_{fdbk}$$

Given this condition, you can calculate the gain of the stage in terms of the resistors (R1 and R2).

The gain of the stage is defined as:

$$Gain = \frac{E_{out}}{E_{in}}$$

$$Since: \quad E_{in} = E_{fdbk}$$

$$Then: \quad Gain = \frac{E_{out}}{E_{fdbk}}$$

The feedback signal (E_{fdbk}) can be shown in terms of the output signal (E_{out}) and the voltage divider (R1 and R2). The voltage divider has the output signal on one end and ground (0 volts) on the other end. The feedback signal is that part of the output signal developed by R1 (at point A). Another way to look at it is that the feedback signal is the amount of output signal left (at point A) after part of the output signal

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has been dropped by R2. In either case, the feedback signal (E_{fdbk}) is the ratio of R1 to the entire voltage divider (R1 + R2) multiplied by the output signal (E_{out}).

Mathematically, the relationship of the output signal, feedback signal, and voltage divider is:

$$E_{fdbk} = \frac{R_1}{R_1 + R_2}(E_{out})$$

If you divide both sides of the equation by E_{out}:

$$\frac{E_{fdbk}}{E_{out}} = \frac{R_1}{R_1 + R_2}$$

By inverting both sides of the equation:

$$\frac{E_{fdbk}}{E_{out}} = \frac{R_1 + R_2}{R_1}$$

Separating the right-hand side:

$$\frac{E_{fdbk}}{E_{out}} = \frac{R_1}{R_1} + \frac{R_2}{R_1}$$

Remember:

$$Gain = \frac{E_{out}}{E_{fdbk}}$$

Therefore, by substitution:

$$Gain = \frac{R_2}{R_1} + 1$$

You can now see that the gain of the noninverting configuration is determined by the resistors. The formula is different from the one used for the inverting configuration, but the gain is still determined by the values of R1 and R2.

BANDWIDTH LIMITATIONS

As with most amplifiers, the gain of an operational amplifier varies with frequency. The specification sheets for operational amplifiers will usually state the open-loop (no feedback) gain for d.c. (or 0 hertz). At higher frequencies, the gain is much lower. In fact, for an operational amplifier, the gain decreases quite rapidly as frequency increases.

Figure 3-17 shows the open-loop (no feedback) frequency-response curve for a typical operational amplifier. As you should remember, bandwidth is measured to the half-power points of a frequency-response curve. The frequency-response curve shows that the bandwidth is only 10 hertz with this

configuration. The UNITY GAIN POINT, where the signal out will have the same amplitude as the signal in (the point at which the gain of the amplifier is 1), is 1 megahertz for the amplifier. As you can see, the frequency response of this amplifier drops off quite rapidly.
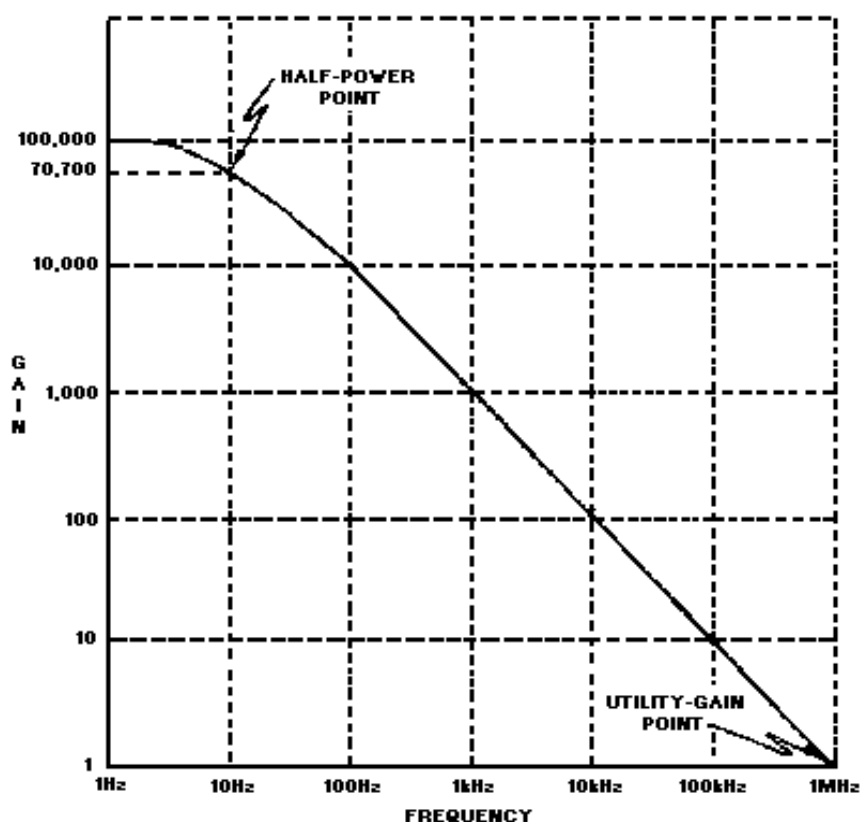

Figure 3-17.—Open-loop frequency-response curve.

Figure 3-17 is the open-loop frequency-response curve. You have been told that most operational amplifiers are used in a closed-loop configuration. When you look at the frequency-response curve for a closed-loop configuration, one of the most interesting and important aspects of the operational amplifier becomes apparent: The use of degenerative feedback increases the bandwidth of an operational amplifier circuit.

This phenomenon is another example of the difference between the operational amplifier itself and the operational-amplifier circuit (which includes the components in addition to the operational amplifier). You should also be able to see that the external resistors not only affect the gain of the circuit, but the bandwidth as well.

You might wonder exactly how the gain and bandwidth of a closed-loop, operational-amplifier circuit are related. Figure 3-18 should help to show you the relationship. The frequency-response curve shown in figure 3-18 is for a circuit in which degenerative feedback has been used to decrease the circuit gain to 100 (from 100,000 for the operational amplifier). Notice that the half-power point of this curve is just slightly above 10 kilohertz.
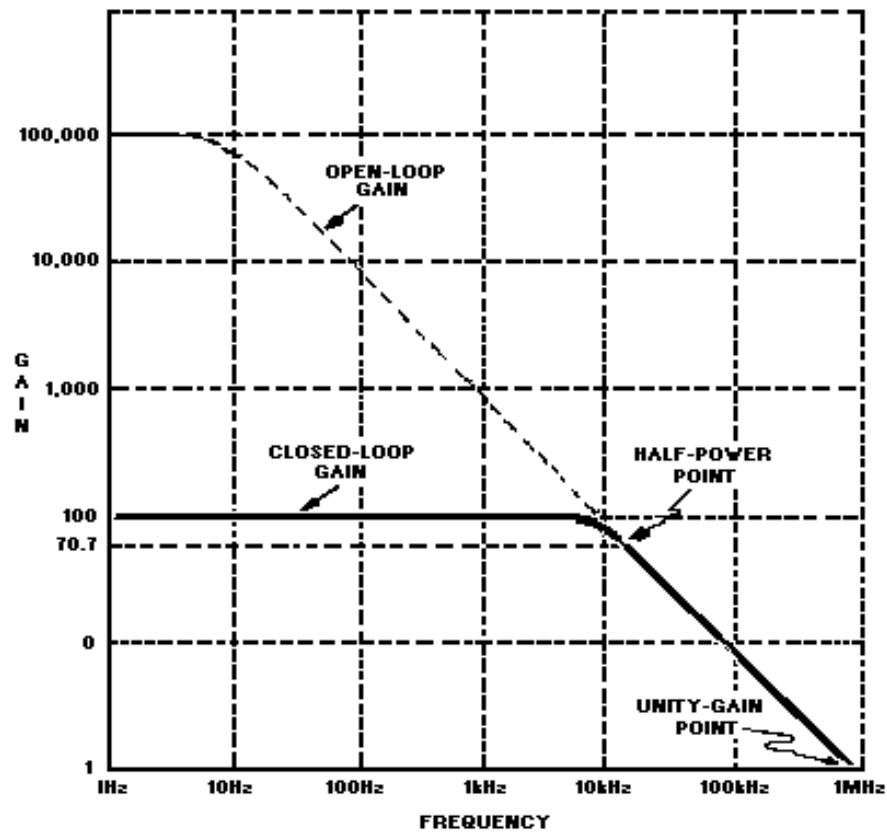
Figure 3-18.—Closed-loop frequency-response curve for gain of 100.

Now look at figure 3-19. In this case, more feedback has been used to decrease the gain of the circuit to 10. Now the bandwidth of the circuit is extended to about 100 kilohertz.
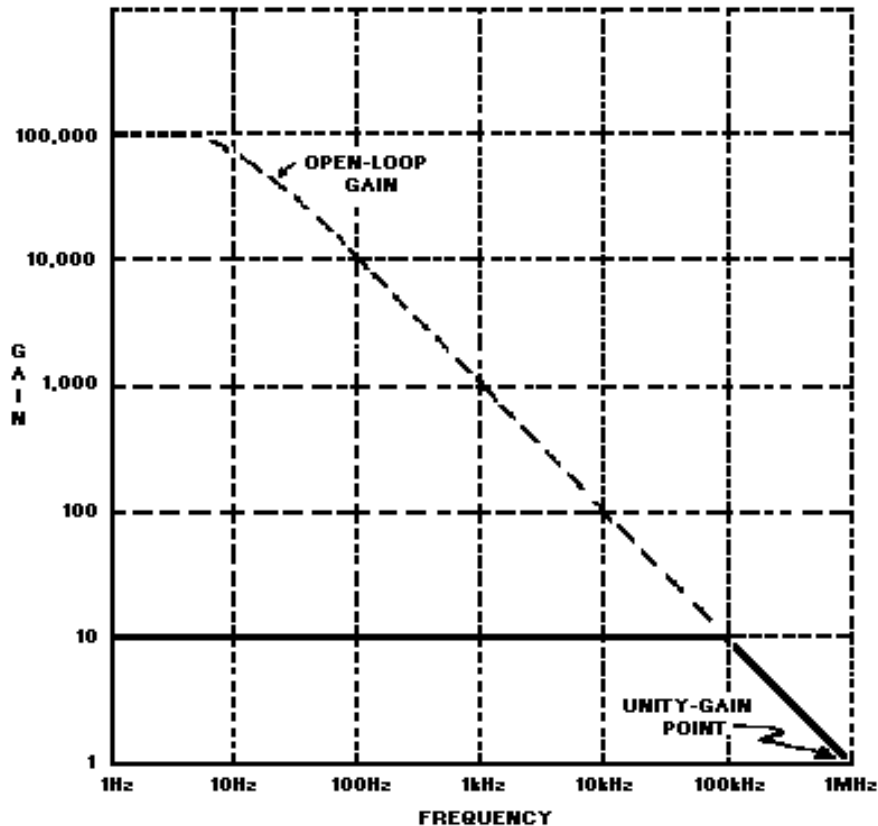
Figure 3-19.—Closed-loop frequency-response curve for gain of 10.

The relationship between circuit gain and bandwidth in an operational-amplifier circuit can be expressed by the GAIN-BANDWIDTH PRODUCT (GAIN × BANDWIDTH = UNITY GAIN POINT). In other words, for operational-amplifier circuits, the gain times the bandwidth for one configuration of an operational amplifier will equal the gain times the bandwidth for any other configuration of the same operational amplifier. In other words, when the gain of an operational-amplifier circuit is changed (by changing the value of feedback or input resistors), the bandwidth also changes. But the gain times the bandwidth of the first configuration will equal the gain times the bandwidth of the second configuration. The following example should help you to understand this concept.

The frequency-response curves shown in figures 3-17, 3-18, and 3-19 have a gain-bandwidth product of 1,000,000. In figure 3-17, the gain is 100,000 and the bandwidth is 10 hertz. The gain-bandwidth product is 100,000 times 10 (Hz), or 1,000,000. In figure 3-18, the gain has been reduced to 100 and the bandwidth increases to 10 kilohertz. The gain-bandwidth product is 100 times 10,000 (Hz) which is also equal to 1,000,000. In figure 3-19 the gain has been reduced to 10 and the bandwidth is 100 kilohertz. The gain-bandwidth product is 10 times 100,000 (Hz), which is 1,000,000. If the gain were reduced to 1, the bandwidth would be 1 megahertz (which is shown on the frequency-response curve as the unity-gain point) and the gain-bandwidth product would still be 1,000,000.

Q-19. What does the term "closed-loop" mean in the closed-loop configuration of an operational amplifier?

In answering Q20, Q21, and Q23, select the correct response from the choices given in the parentheses.

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Q-20.   *In a closed-loop configuration the output signal is determined by (the input signal, the feedback signal, both).*

Q-21.   *In the inverting configuration, the input signal is applied to the (a) (inverting, noninverting) input and the feedback signal is applied to the (b) (inverting, noninverting) input.*

Q-22.   *In the inverting configuration, what is the voltage (for all practical purposes) at the inverting input to the operational amplifier if the input signal is a 1-volt, peak-to-peak sine wave?*

Q-23.   *In the inverting configuration when the noninverting input is grounded, the inverting input is at (signal, virtual) ground.*

Q-24.   *In a circuit such as that shown in figure 3-15, if R1 has a value of 100 ohms and R2 has a value of 1 kilohm and the input signal is at a value of + 5 millivolts, what is the value of the output signal?*

Q-25.   *If the unity-gain point of the operational amplifier used in question 24 is 500 kilohertz, what is the bandwidth of the circuit?*

Q-26.   *In a circuit such as that shown in figure 3-16, if R1 has a value of 50 ohms and R2 has a value of 250 ohms and the input signal has a value of +10 millivolts, what is the value of the output signal?*

Q-27.   *If the open-loop gain of the operational amplifier used in question 26 is 200,000 and the open-loop bandwidth is 30 hertz, what is the closed loop bandwidth of the circuit?*

APPLICATIONS OF OPERATIONAL AMPLIFIERS

Operational amplifiers are used in so many different ways that it is not possible to describe all of the applications. Entire books have been written on the subject of operational amplifiers. Some books are devoted entirely to the applications of operational amplifiers and are not concerned with the theory of operation or other circuits at all. This module, as introductory material on operational amplifiers, will show you only two common applications of the operational amplifier: the summing amplifier and the difference amplifier. For ease of explanation the circuits shown for these applications will be explained with d.c. inputs and outputs, but the circuit will work as well with a.c. signals.

Summing Amplifier (Adder)

Figure 3-20 is the schematic of a two-input adder which uses an operational amplifier. The output level is determined by adding the input signals together (although the output signal will be of opposite polarity compared to the sum of the input signals).
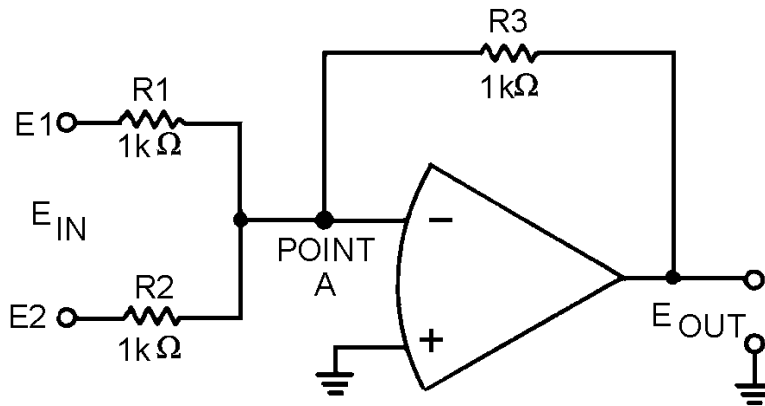
Figure 3-20.—Two-input adder.

If the signal on input number one (E1) is +3 volts and the signal on input number two (E2) is +4 volts, the output signal (E_{out}) should be −7 volts [(+3 V) + (+4 V) = +7 V and change the polarity to get −7 V].

With +3 volts at E1 and 0 volts at point A (which is at virtual ground), the current through R1 must be 3 milliamperes.

Mathematically:

$$I_{R1} = \frac{E_1}{R_1}$$

$$I_{R1} = \frac{+3V}{1k\Omega}$$

$$I_{R1} = +3mA$$

(The + sign indicates a current flow from right to left.)

By the same sort of calculation, with +4 volts at E2 and 0 volts at point A the current through R2 must be 4 milliamps.

This means that a total of 7 milliamps is flowing from point A through R1 and R2. If 7 milliamps is flowing from point A, then 7 milliamps must be flowing into point A. The 7 milliamps flowing into point A flows through R3 causing 7 volts to be developed across R3. With point A at 0 volts and 7 volts developed across R3, the voltage potential at E_{out} must be a −7 volts. Figure 3-21 shows these voltages and currents.
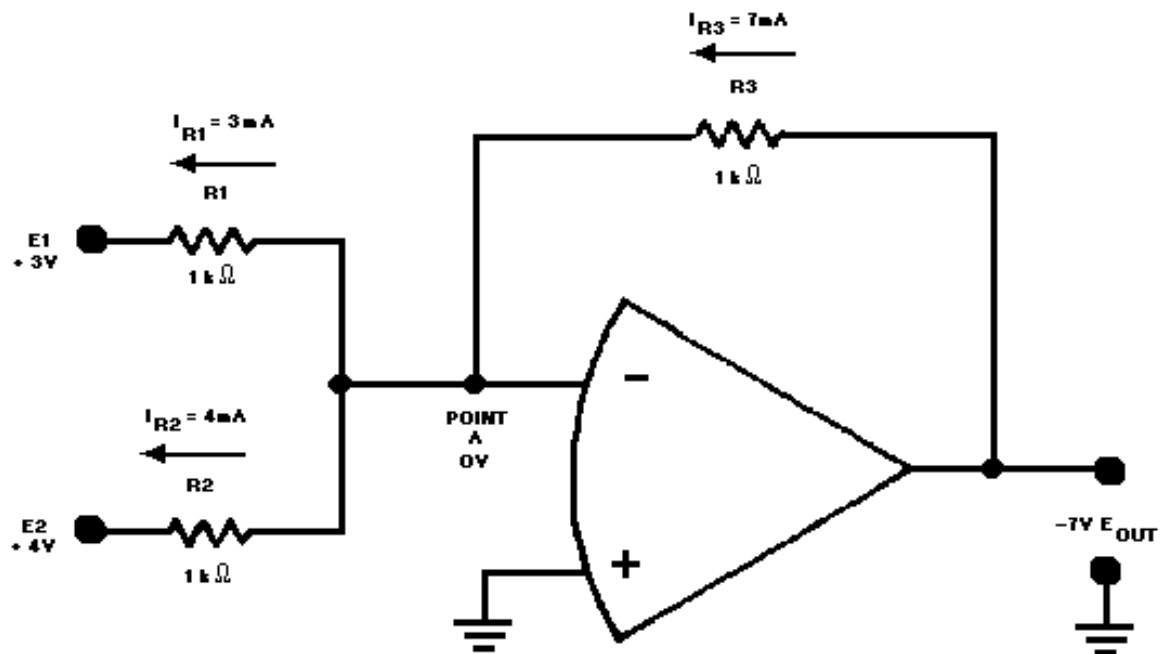
Figure 3-21.—Current and voltage in a two-input adder.

An adder circuit is not restricted to two inputs. By adding resistors in parallel to the input terminals, any number of inputs can be used. The adder circuit will always produce an output that is equal to the sum of the input signals but opposite in polarity. Figure 3-22 shows a five-input adder circuit with voltages and currents indicated.

The table in the figure:

E1	+2V	I_{R1}	2mA
E2	+1V	I_{R2}	1mA
E3	+6V	I_{R3}	6mA
E4	0V	I_{R4}	—
E5	+4V	I_{R5}	4mA
E_{OUT}	-13V	I_{R6}	13mA
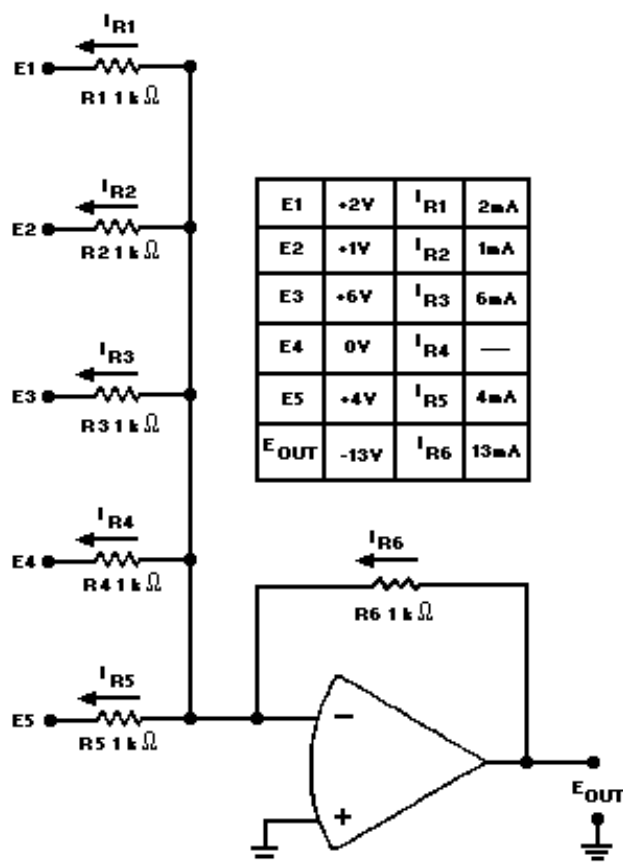
Figure 3-22.—Five-input adder.

The previous circuits have been adders, but there are other types of summing amplifiers. A summing amplifier can be designed to amplify the results of adding the input signals. This type of circuit actually multiplies the sum of the inputs by the gain of the circuit.

Mathematically (for a three-input circuit):

$$E_{out} = gain\ (E1 + E2 + E3)$$

If the circuit gain is -10:

$$E_{out} = -10\ (E1 + E2 + E3)$$

The gain of the circuit is determined by the ratio between the feedback resistor and the input resistors. To change figure 3-20 to a summing amplifier with a gain of -10, you would replace the feedback resistor (R3) with a 10-kilohm resistor. This new circuit is shown in figure 3-23.
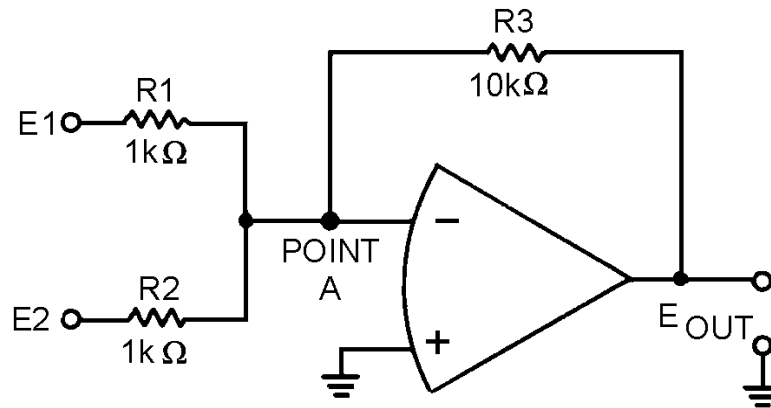
Figure 3-23.—Summing amplifier.

If this circuit is designed correctly and the input voltages (E1 and E2) are +2 volts and +3 volts, respectively, the output voltage (E_{out}) should be:

$$E_{out} = \text{gain } (E1 + E2)$$
$$E_{out} = -10 \left[(+2V) + (+3V) \right]$$
$$E_{out} = -10 (+5)$$
$$E_{out} = -50V$$

To see if this output (−50 V) is what the circuit will produce with the inputs given above, start by calculating the currents through the input resistors, R1 and R2 (remember that point A is at virtual ground):

$$I_{R1} = \frac{E_1}{R_1}$$

$$I_{R1} = \frac{2V}{1k\Omega}$$

$$I_{R1} = 2mA$$

$$I_{R2} = \frac{E_2}{R_2}$$

$$I_{R2} = \frac{3V}{1k\Omega}$$

$$I_{R2} = 3mA$$

Next, calculate the current through the feedback resistor (R3):

$$I_{R3} = -(I_{R1} + I_{R2})$$
$$I_{R3} = -(2 \text{ mA} + 3 \text{ mA})$$
$$I_{R3} = -5 \text{ mA}$$

(The minus sign indicates current flow from left to right.)

Finally, calculate the voltage dropped across R3 (which must equal the output voltage):

$$E_{out} = (I_{R3} \times R3)$$
$$E_{out} = (-5 \text{ mA} \times 10 \text{ k}\Omega)$$
$$E_{out} = -50 \text{ V}$$

As you can see, this circuit performs the function of adding the inputs together and multiplying the result by the gain of the circuit.

One final type of summing amplifier is the SCALING AMPLIFIER. This circuit multiplies each input by a factor (the factor is determined by circuit design) and then adds these values together. The factor that is used to multiply each input is determined by the ratio of the feedback resistor to the input resistor. For example, you could design a circuit that would produce the following output from three inputs (E1, E2, E3):

$$-[(2 \times E1) + (4 \times E2) + (3 \times E3)]$$

Using input resistors R1 for input number one (E1), R2 for input number two (E2), R3 for input number three (E3), and R4 for the feedback resistor, you could calculate the values for the resistors:

$$2 = \frac{R_4}{R_1}$$

$$4 = \frac{R_4}{R_2}$$

$$3 = \frac{R_4}{R_3}$$

Any resistors that will provide the ratios shown above could be used. If the feedback resistor (R4) is a 12-kilohm resistor, the values of the other resistors would be:

$$2 = \frac{12 \text{ k}\Omega}{R1}$$

$$2(R1) = 12 \text{ k}\Omega$$

$$R1 = 6 \text{ k}\Omega$$

$$4 = \frac{12 \text{ k}\Omega}{R2}$$

$$4(R2) = 12 \text{ k}\Omega$$

$$R2 = 3 \text{ k}\Omega$$

$$3 = \frac{12 \text{ k}\Omega}{R3}$$

$$3(R3) = 12 \text{ k}\Omega$$

$$R3 = 4 \text{ k}\Omega$$

Figure 3-24 is the schematic diagram of a scaling amplifier with the values calculated above.
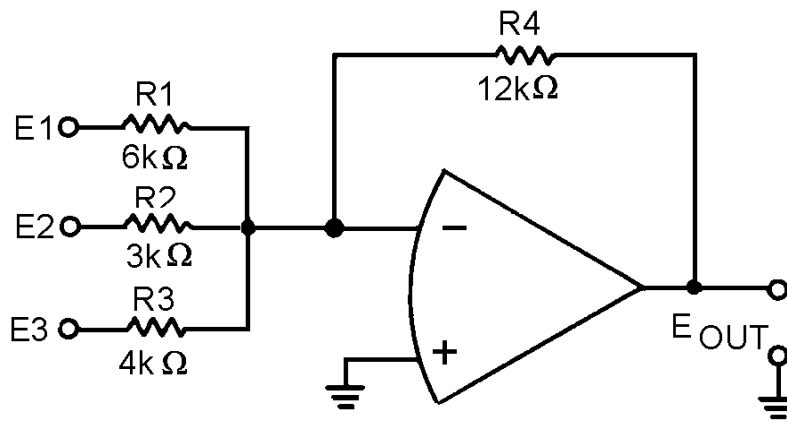
Figure 3-24.—Scaling amplifier.

To see if the circuit will produce the desired output, calculate the currents and voltages as done for the previous circuits.

With:

$$E1 = +12V$$
$$E2 = +3V$$
$$E3 = +8V$$

the output should be:

$$E_{out} = -[(2 \times E1) + (4 \times E2) + (3 \times E3)]$$
$$E_{out} = -[(2 \times +12\,V) + (4 \times +3\,V) + (3 \times +8\,V)]$$
$$E_{out} = -[(+24\,V) + (+12\,V) + (+24\,V)]$$
$$E_{out} = -60\,V$$

Calculate the current for each input:

$$I_{R1} = \frac{E_1}{R_1}$$

$$I_{R1} = \frac{+12V}{6k\Omega}$$

$$I_{R1} = +2mA$$

$$I_{R2} = \frac{E_2}{R_2}$$

$$I_{R2} = \frac{+3V}{3k\Omega}$$

$$I_{R2} = +1mA$$

$$I_{R3} = \frac{E3}{R3}$$

$$I_{R3} = \frac{+8V}{4k\Omega}$$

$$I_{R3} = +2mA$$

$$I_{R4} = -(I_{R1} + I_{R2} + I_{R3})$$

$$I_{R4} = -(2mA + 1mA + 2mA)$$

$$I_{R4} = -5mA$$

Calculate the output voltage:

$$E_{out} = E_{R4}$$
$$E_{out} = I_{R4} \times R_4$$
$$E_{out} = (-5mA \times 12k\Omega$$
$$E_{out} = -60V$$

You have now seen how an operational amplifier can be used in a circuit as an adder, a summing amplifier, and a scaling amplifier.

Difference Amplifier (Subtractor)

A difference amplifier will produce an output based on the difference between the input signals. The subtractor circuit shown in figure 3-25 will produce the following output:

$$E_{out} = E2 - E1$$
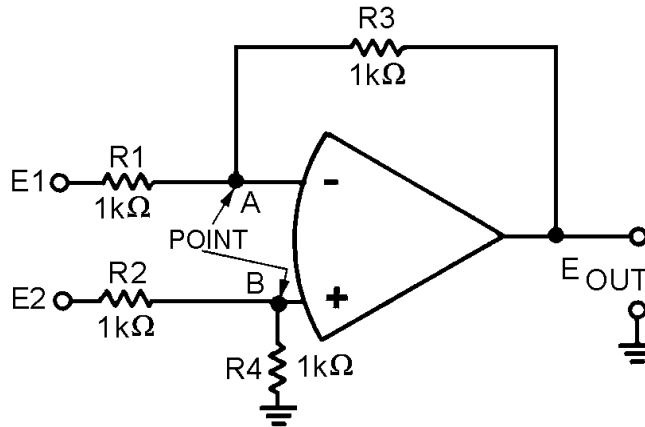
Figure 3-25.—Subtractor circuit.

Normally, difference amplifier circuits have the ratio of the inverting input resistor to the feedback resistor equal to the ratio of the noninverting input resistors. In other words, for figure 3-25:

$$\frac{R1}{R3} = \frac{R2}{R4}$$

and, by inverting both sides:

$$\frac{R3}{R1} = \frac{R4}{R2}$$

For ease of explanation, in the circuit shown in figure 3-25 all the resistors have a value of 1 kilohm, but any value could be used as long as the above ratio is true. For a subtractor circuit, the values of R1 and R3 must also be equal, and therefore, the values of R2 and R4 must be equal. It is NOT necessary that the value of R1 equal the value of R2.

Using figure 3-25, assume that the input signals are:

$$E1 = +3V$$
$$E2 = +12V$$

The output signal should be:

$$E_{out} = E2 - E1$$

$$E_{out} = (+12V) - (+3V)$$

$$E_{out} = +9V$$

To check this output, first compute the value of R2 plus R4:

$$R_2 + R_4 = 1k\Omega + 1k\Omega$$
$$R_2 + R_4 = 2k\Omega$$

With this value, compute the current through R2 (I_{R2}):

$$I_{R2} = \frac{E2}{R_2 + R_4}$$

$$I_{R2} = \frac{+12V}{2k\Omega}$$

$$I_{R2} = +6mA$$

(indicating current flow from left to right)

Next, compute the voltage drop across R2 (E_{R2}):

$$E_{R2} = R_2 \times I_{R2}$$
$$E_{R2} = 1k\Omega \times (+6mA)$$
$$E_{R2} = +6V$$

Then compute the voltage at point B:

Then compute the voltage at point B:

$$\text{Voltage at point B} = E2 - E_{R2}$$
$$\text{Voltage at point B} = (+12V) - (+6V)$$
$$\text{Voltage at point B} = +6V$$

Since point B and point A will be at the same potential in an operational amplifier:

$$\text{Voltage at point A} = +6V$$

Now compute the voltage developed by R1 (E_{R1}):

$$E_{R1} = (\text{voltage at point A}) - (E1)$$
$$E_{R1} = (+6V) - (+3V)$$
$$E_{R1} = +3V$$

Compute the current through R1 (I_{R1}):

$$I_{R1} = \frac{E_{R1}}{R_1}$$

$$I_{R1} = \frac{+3V}{1k\Omega}$$

$$I_{R1} = +3mA$$

$$\text{Since: } I_{R1} = I_{R3}$$

$$\text{Then: } I_{R3} = +3mA$$

Compute the voltage developed by R3 (E_{R3}):

$$E_{R3} = (R_3) \times (I_{R3})$$
$$E_{R3} = (1k\Omega) \times (+3mA)$$
$$E_{R3} = +3V$$

Add this to the voltage at point A to compute the output voltage (E_{out}):

$$E_{out} = (E_{R3}) + (\text{voltage at point A})$$
$$E_{out} = (+3V) \times (+6V)$$
$$E_{out} = +9V$$

As you can see, the circuit shown in figure 3-25 functions as a subtractor. But just as an adder is only one kind of summing amplifier, a subtractor is only one kind of difference amplifier. A difference amplifier can amplify the difference between two signals. For example, with two inputs (E1 and E2) and a gain of five, a difference amplifier will produce an output signal which is:

$$E_{out} = 5\,(E2 - E1)$$

The difference amplifier that will produce that output is shown in figure 3-26. Notice that this circuit is the same as the subtractor shown in figure 3-25 except for the values of R3 and R4. The gain of this difference amplifier is:
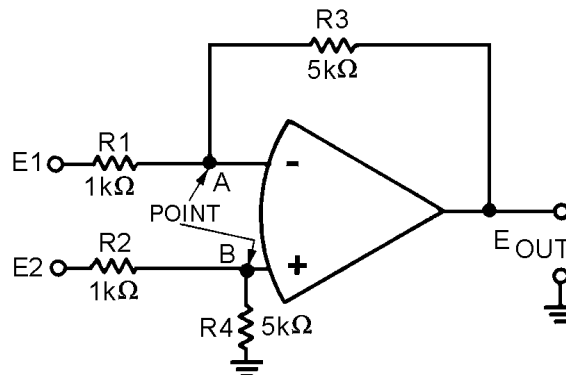
Figure 3-26.—Difference amplifier.

$$\text{Gain} = \frac{R3}{R1}$$

$$\text{Gain} = \frac{5\ k\Omega}{1\ k\Omega}$$

$$\text{Gain} = 5$$

Then, for a difference amplifier:

$$\text{Gain} = \frac{R3}{R1} = \frac{R4}{R2}$$

With the same inputs that were used for the subtractor, (E1 = + 3 V; E2 = + 12 V) the output of the difference amplifier should be five times the output of the subtractor (E_{out} = + 45 V).

Following the same steps used for the subtractor:

First compute the value of R2 plus R4:

$$R2 + R4 = 1\ k\Omega + 5\ k\Omega$$

$$R2 + R4 = 4\ k\Omega$$

With this value, compute the current through R2 (I_{R2}):

$$I_{R2} = \frac{E2}{R_2 + R_4}$$

$$I_{R2} = \frac{+12V}{6k\Omega}$$

$$I_{R2} = +2mA$$

Next, compute the voltage drop across R2 (E_{R2}):

$$E_{R2} = (R_2) \times (I_{R2})$$
$$E_{R2} = (1k\Omega) \times (+2mA)$$
$$E_{R2} = +2V$$

Then, compute the voltage at point B:

$$\text{Voltage at point B} = E2 - E_{R2}$$
$$\text{Voltage at point B} = (+12V) - (+2V)$$
$$\text{Voltage at point B} = +10V$$

Since point A and point B will be at the same potential in an operational amplifier:

$$\text{Voltage at point A} = +10V$$

Now compute the voltage developed by R1 (E_{R1}):

$$
\begin{aligned}
E_{R1} &= \text{(voltage at point A)} - \text{(E1)} \\
E_{R1} &= (+10V) - (+3\,V) \\
E_{R1} &= +7\,V
\end{aligned}
$$

Compute the current through R1 (I_{R1}):

$$
I_{R1} = \frac{E_{R1}}{R_1}
$$

$$
I_{R1} = \frac{+7V}{k\Omega}
$$

$$
I_{R1} = +7mA
$$

$$
\text{Since: } I_{R1} = I_{R3}
$$

$$
\text{Then: } I_{R3} = +7mA
$$

Compute the voltage developed by R3 (E_{R3}):

$$
E_{R3} = R3 \times I_{R3}
$$

$$
E_{R3} = (5k\Omega) \times (+7mA)
$$

$$
E_{R3} = +35V
$$

Add this voltage to the voltage at point A to compute the output voltage (E_{out}):

$$
E_{out} = (E_{R3}) + \text{(voltage at point A)}
$$

$$
E_{out} = (+35V) + (+10V)
$$

$$
E_{out} = +45V
$$

This was the output desired, so the circuit works as a difference amplifier.

Q-28.   *What is the difference between a summing amplifier and an adder circuit?*

Q-29.   *Can a summing amplifier have more than two inputs?*

Q-30.   *What is a scaling amplifier?*

Refer to figure 3-27 in answering Q31 through Q33.
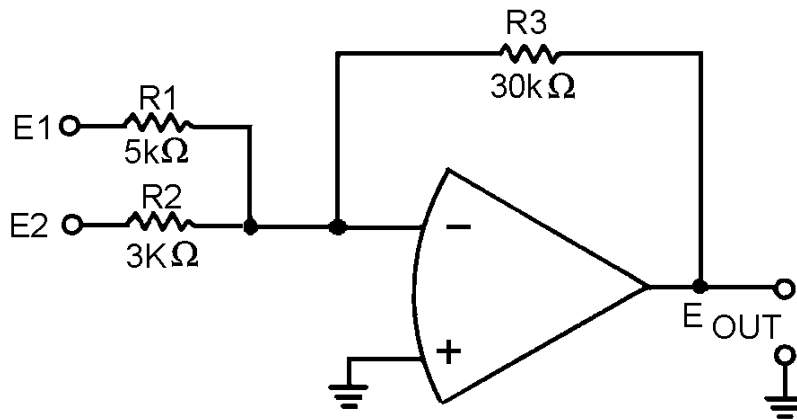
Figure 3-27.—Circuit for Q31 through Q33.

Q-31.   *What type of circuit is figure 3-27?*

Q-32.   *If: E1 = +2V, and: E2 = +6V, then E_{out} = ?*

Q-33.   *What is the difference in potential between the inverting (-) and noninverting (+) inputs to the operational amplifier when: E1 = +6V, and E2 = +2V*

Q-34.   *What is the difference between a subtractor and a difference amplifier?*

Q-35.   *Can a difference amplifier have more than two inputs?*

Refer to figure 3-28 in answering Q36 through Q38.
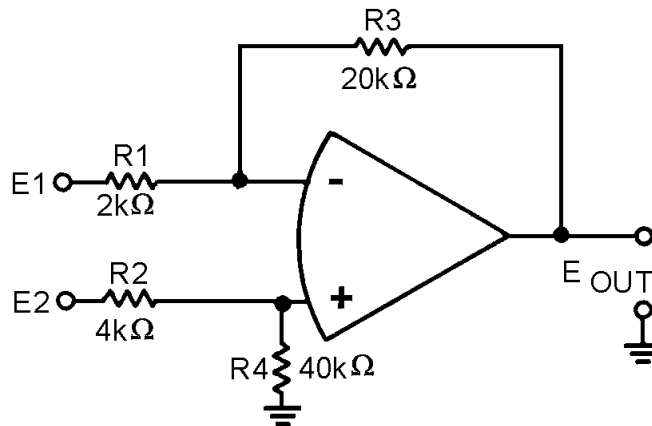
Figure 3-28.—Circuit for Q36 through Q38.

Q-36.   *What type of circuit is figure 3-28?*

Q-37.   *If: E1 = +5V, and: E2 = +11V, then E_{out} = ?*

Q-38.   *What is the difference in potential between the inverting (−) and noninverting (+) inputs to the operational amplifier when: E1 = +2V, and E2 = +4V*

MAGNETIC AMPLIFIERS

You have now been shown various ways that electron tubes (*NEETS, Module 6*) and transistors (*NEETS, Module 7)* can be used to amplify signals. You have also been shown the way in which this is done. There is another type of amplifier in use—the MAGNETIC AMPLIFIER, sometimes called the MAG AMP.

The magnetic amplifier has certain advantages over other types of amplifiers. These include (1) high efficiency (up to 90 percent); (2) reliability (long life, freedom from maintenance, reduction of spare parts inventory); (3) ruggedness (shock and vibration resistance, high overload capability, freedom from effects of moisture); and (4) no warm-up time. The magnetic amplifier has no moving parts and can be hermetically sealed within a case similar to the conventional dry-type transformer.

However, the magnetic amplifier has a few disadvantages. For example, it cannot handle low-level signals; it is not useful at high frequencies; it has a time delay associated with the magnetic effects; and the output waveform is not an exact reproduction of the input waveform (poor fidelity).

The magnetic amplifier is important, however, to many phases of naval engineering because it provides a rugged, trouble-free device that has many applications aboard ship and in aircraft. These applications include throttle controls on the main engines of ships; speed, frequency, voltage, current, and temperature controls on auxiliary equipment; and fire control, servomechanisms, and stabilizers for guns, radar, and sonar equipment.

As stated earlier, the magnetic amplifier does not amplify magnetism, but uses electromagnetism to amplify a signal. It is a power amplifier with a very limited frequency response. Technically, it falls into the classification of an audio amplifier; but, since the frequency response is normally limited to 100 hertz and below, the magnetic amplifier is more correctly called a low-frequency amplifier.

The basic principle of a magnetic amplifier is very simple. (Remember, all amplifiers are current-control devices.) A magnetic amplifier uses a changing inductance to control the power delivered to a load.

BASIC OPERATION OF A MAGNETIC AMPLIFIER

Figure 3-29 shows a simple circuit with a variable inductor in series with a resistor (representing a load). The voltage source is 100 volts at 60 hertz.
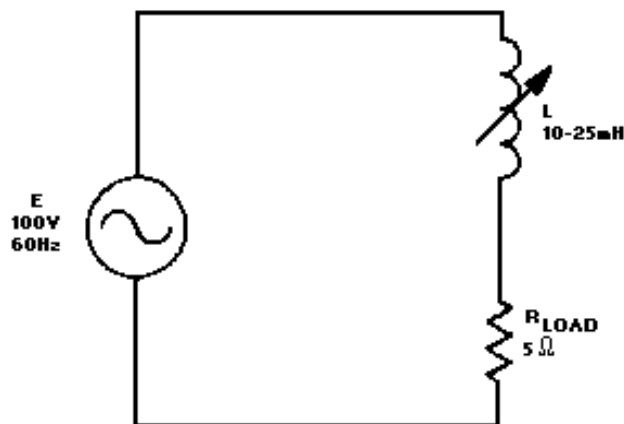

Figure 3-29.—Variable inductor in series with a load.

What happens when the inductance <u>decreases</u>? The end result is that the power in the load (true power) <u>increases</u>. Why? Look at the following formulas and see how each is affected by a decrease in inductance.

$$X_L = 2\pi fL \qquad \text{(inductive reactance in the circuit)}$$

$$Z = \sqrt{X_L^2 + R^2} \qquad \text{(impedance in the circuit)}$$

$$I = \frac{E}{Z} \qquad \text{(current in the circuit)}$$

$$\text{True power} = I^2 R \qquad \text{(true power or power in the load)}$$

(True power is covered in *NEETS, Module 2—Introduction to Alternating Current and Transformers*.)

As inductance (L) decreases, X_L decreases. As X_L decreases, Z decreases. As Z decreases, I increases. Finally, as I increases, true power increases.

This general conclusion can be confirmed by using some actual values of inductance in the formulas along with other values from figure 3-29.

If the value of inductance is 23 millihenries, the formulas yield the following values:

$$X_L = 2\pi fL$$
$$X_L = (2)(3.14)(60Hz)(23mH)$$
$$X_L = 8.67\Omega \text{ (rounded off)}$$

$$Z = \sqrt{X_L^2 + R^2}$$

$$Z = \sqrt{(8.67\Omega)^2 + (5\Omega)^2}$$

$$Z = \sqrt{100.1689\Omega}$$

$$Z = 10\Omega \text{ (rounded off)}$$

$$I = \frac{E}{Z}$$

$$I = \frac{100V}{10\Omega}$$

$$I = 10A$$

$$\text{True Power} = I^2 R$$
$$\text{True Power} = (10A)^2 + (5\Omega)$$
$$\text{True Power} = 500 \text{ watts}$$

Now, if the value of inductance is decreased to 11.7 millihenries, the formulas yield the following values:

$$X_L = 2\pi fL$$
$$X_L = (2)(3.14)(60Hz)(11.7mH)$$
$$X_L = 4.41\Omega \text{ (rounded off)}$$

$$Z = \sqrt{X_L{}^2 + R^2}$$

$$Z = \sqrt{(4.41\Omega)^2 + (5\Omega)^2}$$

$$Z = \sqrt{44.4481\Omega}$$

$$Z = 6.67\Omega \text{ (rounded off)}$$

$$I = \frac{E}{Z}$$

$$I = \frac{100V}{6.67\Omega}$$

$$I = 15A \text{ (rounded off)}$$

$$\text{True Power} = I^2R$$
$$\text{True Power} = (15A)^2 + (5\Omega)$$
$$\text{True Power} = 1125\text{ watts}$$

So a decrease in inductance of 11.3 millihenries (23 mH—11.7 mH) causes an increase in power to the load (true power) of 625 watts (1125 W—500 W). If it took 1 watt of power to change the inductance by 11.3 millihenries (by some electrical or mechanical means), figure 3-29 would represent a power amplifier with a gain of 625.

Q-39. What is the frequency classification of a magnetic amplifier?

Q-40. What is the basic principle of a magnetic amplifier?

Q-41. If inductance increases in a series LR circuit, what happens to true power?

METHODS OF CHANGING INDUCTANCE

Since changing the inductance of a coil enables the control of power to a load, what methods are available to change the inductance? Before answering that question, you should recall a few things about *magnetism and inductors from NEETS, Module 1—Introduction to Matter, Energy, and Direct Current,* chapter 1—*Matter, Energy, and Electricity*; and *Module 2 —Introduction to Alternating Current and Transformers,* chapter 2—*Inductance*.

Permeability was defined as the measure of the ability of a material to act as a path for additional magnetic lines of force. Soft iron was presented as having high permeability compared with air. In fact, the permeability of unmagnetized iron is 5000 while air has a permeability of 1. A nonmagnetized piece of iron has high permeability because the tiny molecular magnets (Weber's Theory) or the directions of electron spin (Domain Theory) are able to be aligned by a magnetic field. As they align, they act as a path for the magnetic lines of force.

Earlier *NEETS* modules state that the inductance of a coil increases directly as the permeability of the core material increases. If a coil is wound around an iron core, the permeability of the core is 5000. Now, if the iron is pulled part way out of the coil of wire, the core is part iron and part air. The permeability of the core decreases. As the permeability of the core decreases, the inductance of the coil decreases. This increases the power delivered to the load (true power). This relationship is shown in figure 3-30.

The system shown in figure 3-30 is not too practical. Even if a motor were used in place of the hand that is shown, the resulting amplifier would be large, expensive, and not easily controlled. If the permeability of a core could be changed by electrical means rather than mechanical, a more practical system would result.
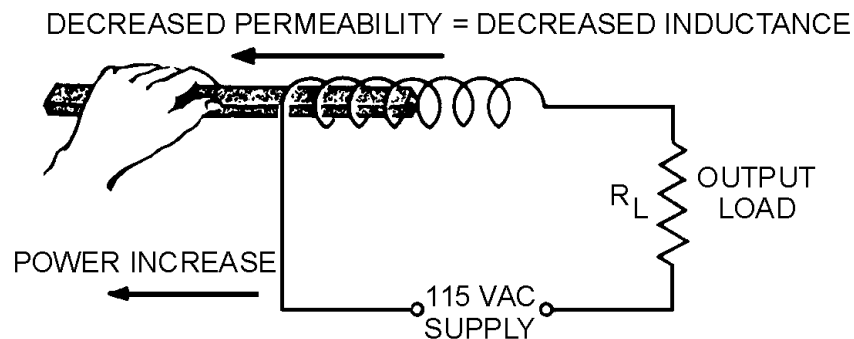
Figure 3-30.—Varying coil inductance with a movable coil.

High permeability depends on there being many molecular magnets (or electron spin directions) that can be aligned to provide a path for magnetic lines of force. If almost all of these available paths are already being used, the material is magnetized and there are no more paths for additional lines of force. The "flux density" (number of lines of force passing through a given area) is as high as it can be. This means that the permeability of the material has decreased. When this condition is reached, the core is said to be SATURATED because it is saturated (filled) with all the magnetic lines of force it can pass. At this point, the core has almost the same value of permeability as air (1) instead of the much higher value of permeability (5000) that it had when it was unmagnetized.

Of course, the permeability does not suddenly change from 5000 to 1. The permeability changes as the magnetizing force changes until saturation is reached. At saturation, permeability remains very low no matter how much the magnetizing force increases. If you were to draw a graph of the flux density compared to the magnetizing force, you would have something similar to the graph shown in figure 3-31. Figure 3-31 also includes a curve representing the value of permeability as the magnetizing force increases. Point "s" in figure 3-31 is the point of saturation. The flux density does not increase above point "s," and the permeability is at a steady, low value.
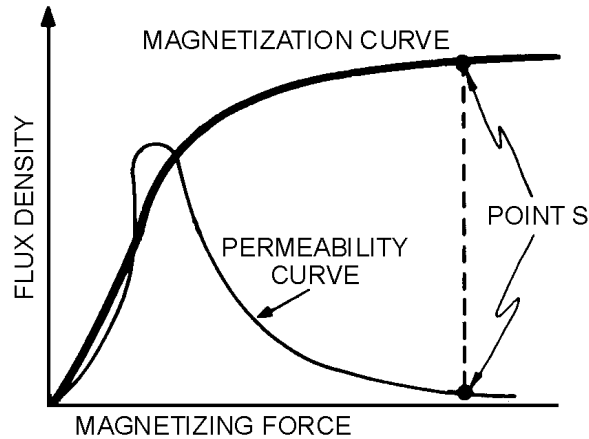
Figure 3-31.—Magnetization and permeability curves.

You have now seen how a change in the magnetizing force causes a change in permeability. The next question is, how do you change the magnetizing force? Magnetizing force is a function of AMPERE-TURNS. (An ampere-turn is the magnetomotive force developed by 1 ampere of current flowing in a coil of one turn.) If you increase the ampere-turns of a coil, the magnetizing force increases. Since it is not practical to increase the number of turns, the easiest way to accomplish this is to increase the current through the coil.

If you increase the current through a coil, you increase the ampere-turns. By increasing the ampere-turns you increase the magnetizing force. At some point, this causes a decrease in the permeability of the core. With the permeability of the core decreased, the inductance of the coil decreases. As said before, a decrease in the inductance causes an increase in power through the load. A device that uses this arrangement is called a SATURABLE-CORE REACTOR or SATURABLE REACTOR.

SATURABLE-CORE REACTOR

A saturable-core reactor is a magnetic-core reactor (coil) whose reactance is controlled by changing the permeability of the core. The permeability of the core is changed by varying a unidirectional flux (flux in one direction) through the core.

Figure 3-32 shows a saturable-core reactor that is used to control the intensity of a lamp. Notice that two coils are wound around a single core. The coil on the left is connected to a rheostat and a battery. This coil is called the control coil because it is part of the control circuit. The coil on the right is connected to a lamp (the load) and an a.c. source. This coil is called the load coil because it is part of the load circuit.

As the wiper (the movable connection) of the rheostat is moved toward the right, there is less resistance in the control circuit. With less resistance, the control-circuit current increases. This causes the amount of magnetism in the core to increase and the inductance of the coil in the load circuit to decrease (because the core is common to both coils). With less inductance in the load circuit, load current increases and the lamp gets brighter.
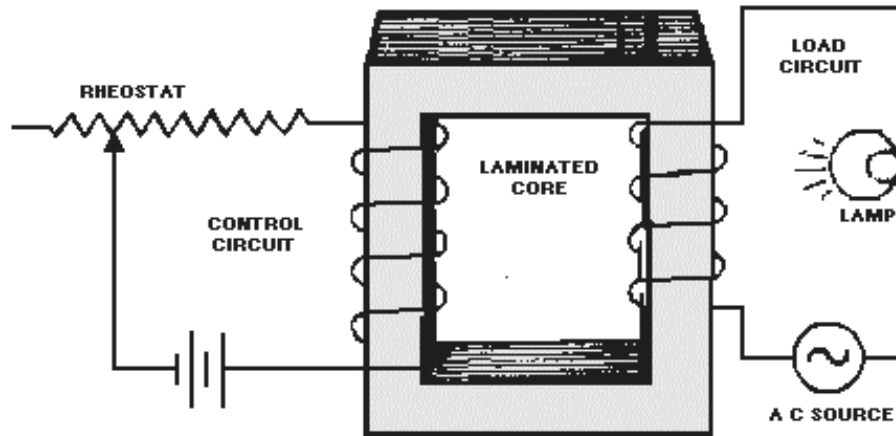
Figure 3-32.—A simple saturable-core reactor circuit.

The schematic diagram of this circuit is shown in figure 3-33. L1 is the schematic symbol for a saturable-core reactor. The control winding is shown with five loops, and the load winding is shown with three loops. The double bar between the inductors stands for an iron core, and the symbol that cuts across the two windings is a saturable-core symbol indicating that the two windings share a saturable core.
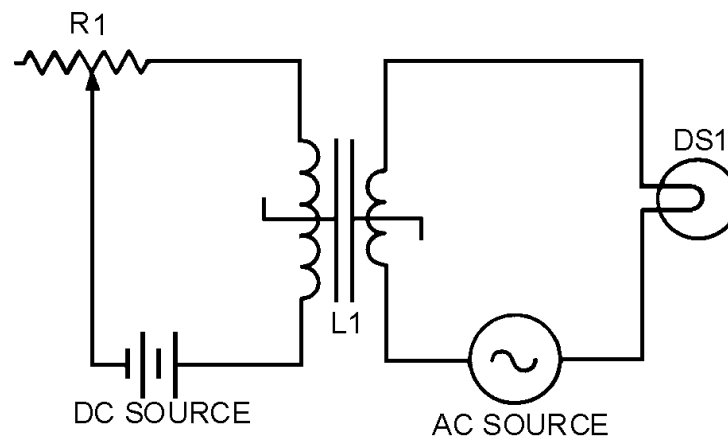

Figure 3-33.—Schematic diagram of a simple saturable-core reactor.

Now that you have seen the basic operation of a saturable-core reactor, there is one other idea to discuss before moving on to the circuitry of a magnetic amplifier. There is a point upon the magnetization curve where the saturable-core reactor should be operated. The ideal operating point is the place in which a small increase in control current will cause a large increase in output power and a small decrease in control current will cause a large decrease in output power. This point is on the flattest portion of the permeability curve (after its peak).

Figure 3-34 shows the magnetization and permeability curves for a saturable-core reactor with the ideal operating point (point "O") indicated. Notice point "O" on the magnetization curve. The portion of the magnetization curve where point "O" is located is called the KNEE OF THE CURVE. The knee of the curve is the point of maximum curvature. It is called the "knee" because it looks like the knee of a leg that is bent. Saturable-core reactors and magnetic amplifiers should be operated on the knee of the magnetization curve.

3-48
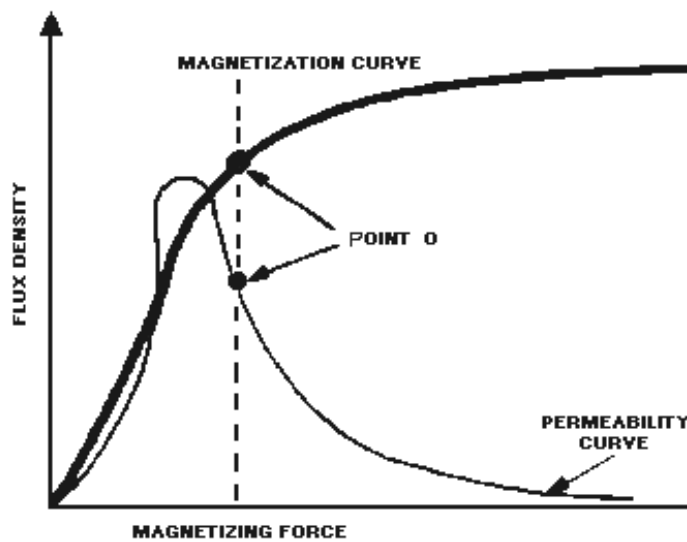
Figure 3-34.—Magnetization and permeability curves with operating point.

When the saturable-core reactor is set at the knee of the magnetization curve, any small increase in control current will cause a large increase in load current. Any small decrease in control current will cause a large decrease in load current. That is why point "O" is the ideal operating point-because small changes in control current will cause large changes in load current. In other words, the saturable-core reactor can amplify the control current. However, a saturable-core reactor is NOT a magnetic amplifier. You will find out a little later how a magnetic amplifier differs from a saturable-core reactor. First you should know a few more things about the saturable-core reactor.

If a d.c. voltage is applied to the control winding of a saturable-core reactor and an a.c. voltage is applied to the load windings, the a.c. flux will aid the d.c. flux on one half cycle and oppose the d.c. flux on the other half cycle. This is shown in figure 3-35. Load flux is indicated by the dashed-line arrows, and control flux is indicated by the solid-line arrows. View (A) shows the load and control flux adding during one half cycle of the a.c. View (B) of the figure shows the load and control flux opposing during the other half cycle of the a.c.
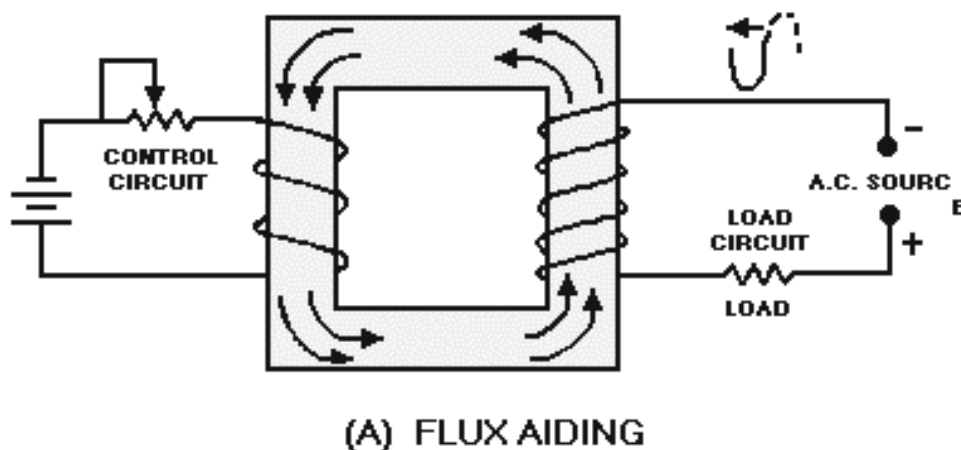
Figure 3-35A.—Flux paths in a saturable-core reactor. FLUX AIDING
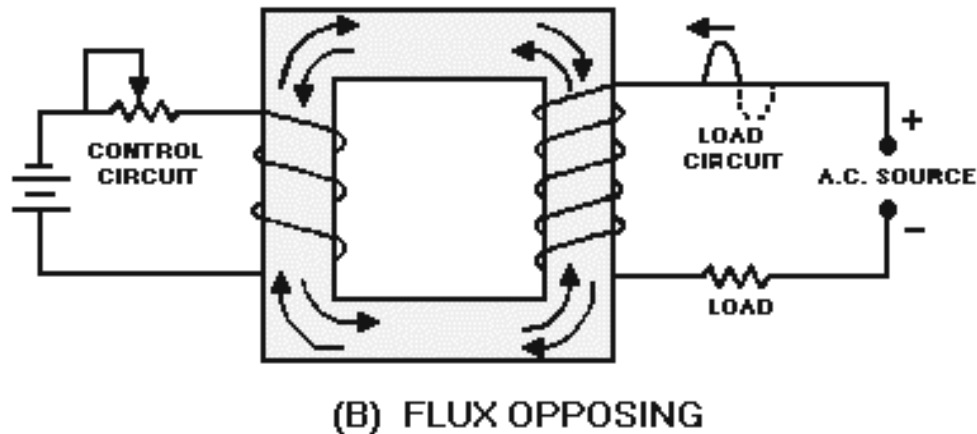
(B) FLUX OPPOSING

Figure 3-35B.—Flux paths in a saturable-core reactor. FLUX OPPOSING

This situation causes the operating point of the saturable-core reactor to shift with the applied a.c. However, the situation would be better if the load flux was not an influence on the control flux. Figure 3-36 shows a circuit in which this is accomplished.

During the first half cycle, the load circuit flux (dashed-line arrows) cancels in the center leg of the core. This is shown in figure 3-36, view (A). As a result, there is no effect upon the flux from the control circuit. During the second half cycle, the polarity of the a.c. (and therefore the polarity of the flux) reverses as shown in view (B). The result is the same as it was during the first half cycle. There is no effect upon the control circuit flux.
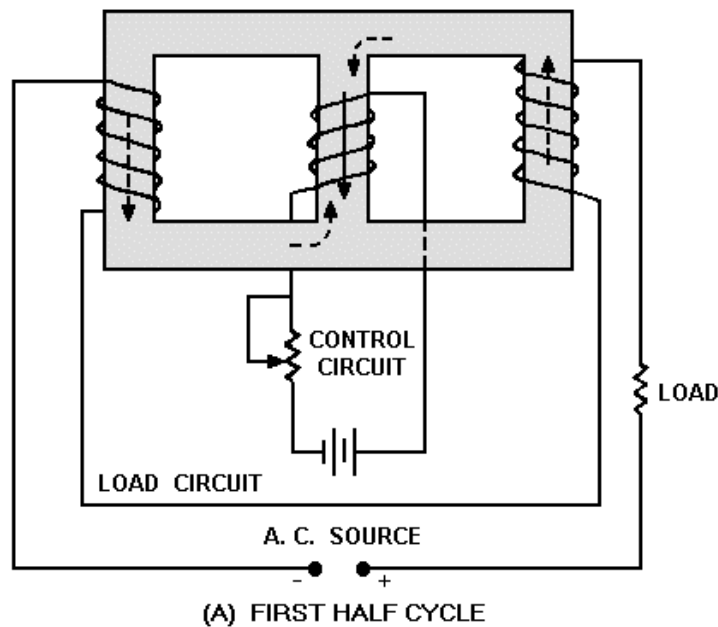
(A) FIRST HALF CYCLE

Figure 3-36A.—Three-legged, saturable-core reactor. FIRST HALF CYCLE
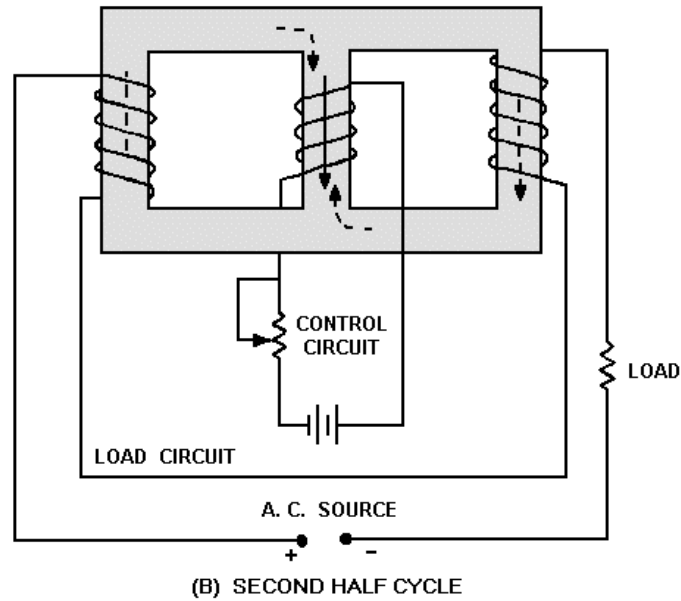
Figure 3-36B.—Three-legged, saturable-core reactor. SECOND HALF CYCLE

Another approach to solving the problem of load flux affecting control flux is shown in figure 3-37. Figure 3-37 shows a toroidal saturable-core reactor. The shape of these cores is a toroid (donut shape). The windings are wound around the cores so that the load flux aids the control flux in one core and opposes the control flux in the other core.

During the first half cycle, the flux aids in the left core and opposes in the right core, as shown in figure 3-37, view (A). During the second half cycle, the flux opposes in the left core and aids in the right core, as shown in view (B). Regardless of the amount of load flux or polarity of the load voltage, there is no net effect of load flux on control flux.
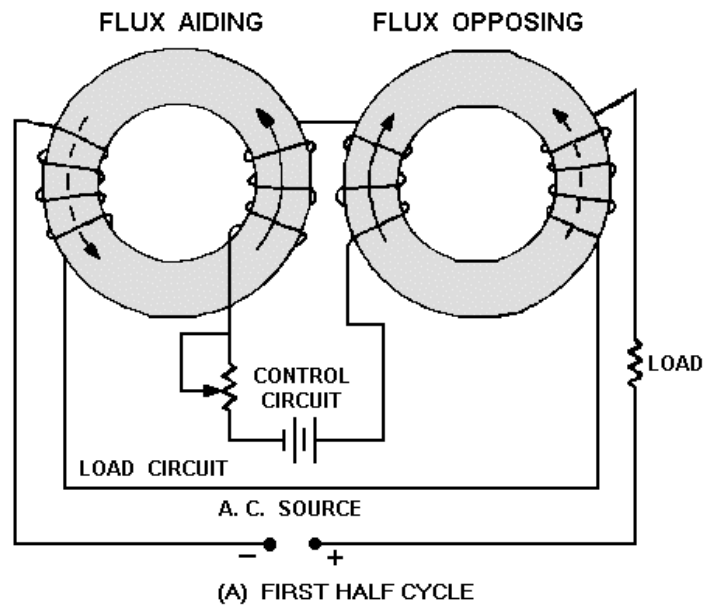
Figure 3-37A.—Toroidal saturable-core reactor. FIRST HALF CYCLE

FLUX OPPOSING   FLUX AIDING

LOAD

CONTROL
CIRCUIT

LOAD CIRCUIT

A. C. SOURCE
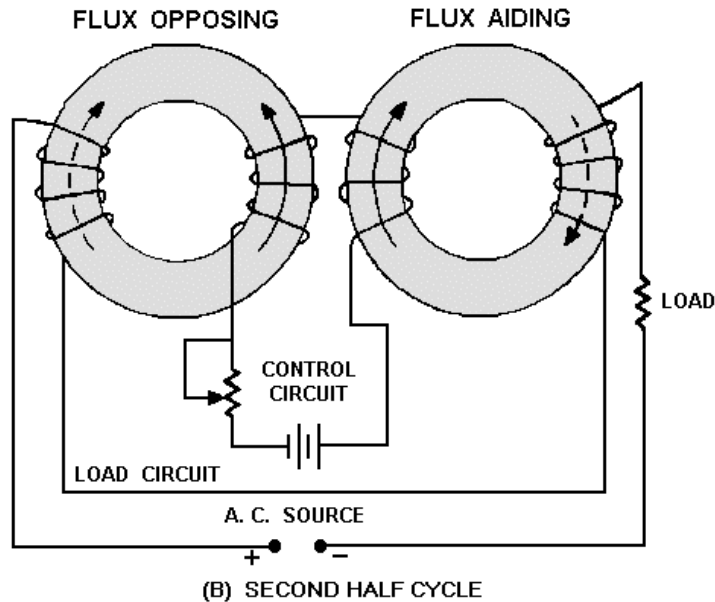
(B) SECOND HALF CYCLE

Figure 3-37B.—Toroidal saturable-core reactor. SECOND HALF CYCLE

Figures 3-36 and 3-37 both represent practical, workable saturable-core reactors. Circuits similar to these are actually used to control lighting in auditoriums or electric industrial furnaces. These circuits are sometimes referred to as magnetic amplifiers, but that is NOT technically correct. A magnetic amplifier differs from a saturable-core reactor in one important aspect: A magnetic amplifier has a rectifier in addition to a saturable-core reactor.

Q-42.   If the permeability of the core of a coil increases, what happens to (a) inductance and (b) true power in the circuit?

Q-43.   What happens to the permeability of an iron core as the current increases from the operating point to a large value?

Q-44.   If two coils are wound on a single iron core, what will a change in current in one coil cause in the other coil?

Q-45.   What symbol in figure 3-33 indicates a saturable core connecting two windings?

SIMPLIFIED MAGNETIC AMPLIFIER CIRCUITRY

If the saturable-core reactor works, why do we need to add a rectifier to produce a magnetic *amplifier? To answer this question, recall that in NEETS, Module 2—Introduction to Alternating Current and Transformers*, you were told about hysteresis loss. Hysteresis loss occurs because the a.c. applied to a coil causes the tiny molecular magnets (or electron-spin directions) to realign as the polarity of the a.c. changes. This realignment uses up power. The power that is used for realignment is a loss as far as the rest of the circuit is concerned. Because of this hysteresis loss in the saturable-core reactor, the power gain is relatively low. A rectifier added to the load circuit will eliminate the hysteresis loss and increase the gain. This is because the rectifier allows current to flow in only one direction through the load coils.

A simple half-wave magnetic amplifier is shown in figure 3-38. This is a half-wave magnetic amplifier because it uses a half-wave rectifier. During the first half cycle of the load voltage, the diode conducts and the load windings develop load flux as shown in view (A) by the dashed-line arrows. The

load flux from the two load coils cancels and has no effect on the control flux. During the second half cycle, the diode does not conduct and the load coils develop no flux, as shown in view (B). The load flux never has to reverse direction as it did in the saturable-core reactor, so the hysteresis loss is eliminated.
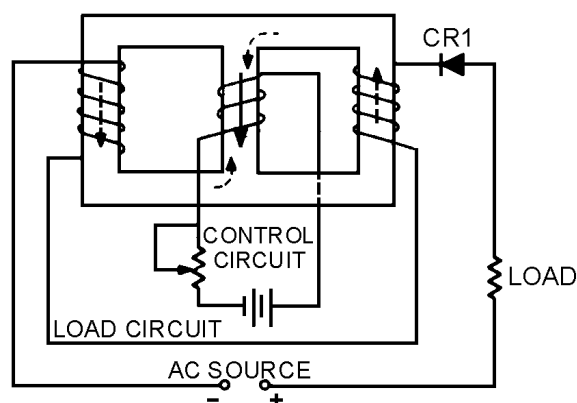
(A) FIRST HALF CYCLE

Figure 3-38A.—Simple half-wave magnetic amplifier. FIRST HALF CYCLE
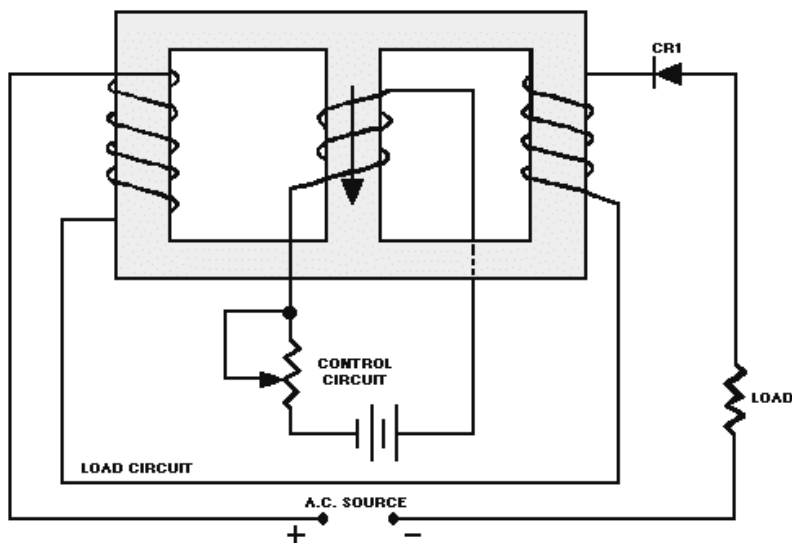
(B) SECOND HALF CYCLE

Figure 3-38B.—Simple half-wave magnetic amplifier. SECOND HALF CYCLE

The circuit shown in figure 3-38 is only able to use half of the load voltage (and therefore half the possible load power) since the diode blocks current during half the load-voltage cycle. A full-wave rectifier used in place of CR1 would allow current flow during the entire cycle of load voltage while still preventing hysteresis loss.

Figure 3-39 shows a simple full-wave magnetic amplifier. The bridge circuit of CR1, CR2, CR3, CR4 allows current to flow in the load circuit during the entire load voltage cycle, but the load current is always in the same direction. This current flow in one direction prevents hysteresis loss.

View (A) shows that during the first half cycle of load voltage, current flows through CR1, the load coils, and CR3. View (B) shows that during the second half cycle, load current flows through CR2, the load coils, and CR4.
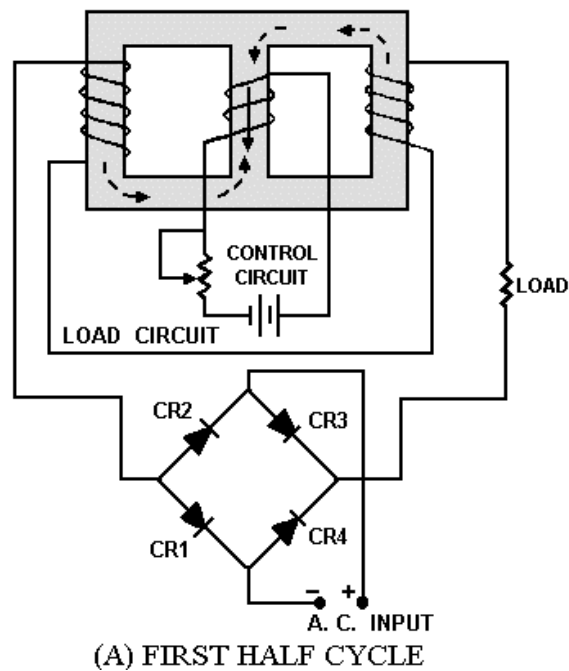
Figure 3-39A.—Simple full-wave magnetic amplifier. FIRST HALF CYCLE
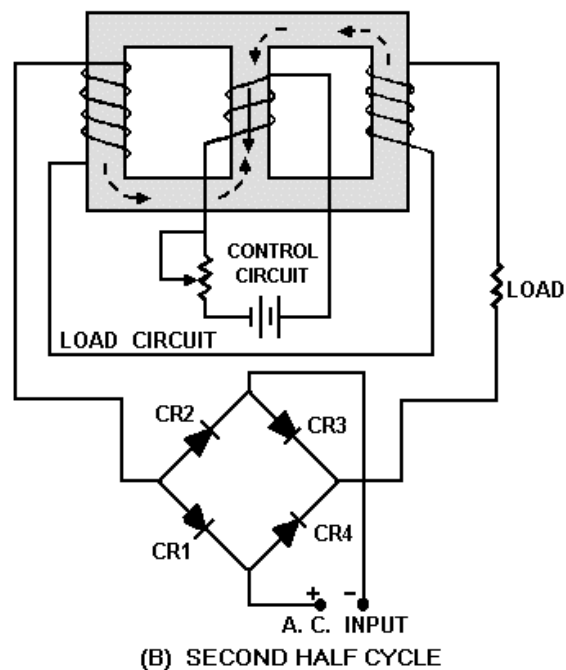
Figure 3-39B.—Simple full-wave magnetic amplifier. SECOND HALF CYCLE

Up to this point, the control circuit of the magnetic amplifier has been shown with d.c. applied to it. Magnetic-amplifier control circuits should accept a.c. input signals as well as d.c. input signals. As shown

earlier in figure 3-34, a saturable-core reactor has an ideal operating point. Some d.c. must always be applied to bring the saturable core to that operating point. This d.c. is called BIAS. the most effective way to apply bias to the saturable core and also allow a.c. input signals to control the magnetic amplifier is to use a bias winding. A full-wave magnetic amplifier with a bias winding is shown in figure 3-40.
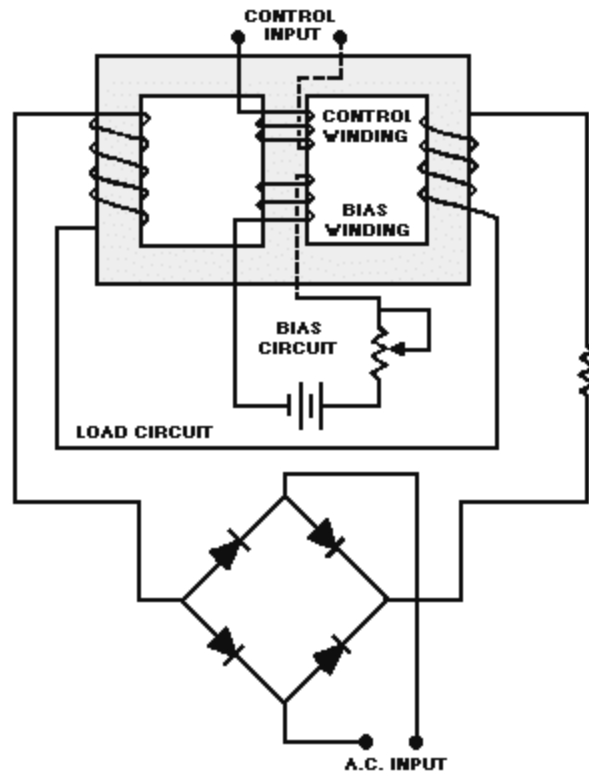
Figure 3-40.—Full-wave magnetic amplifier with bias winding.

In the circuit shown in figure 3-40, the bias circuit is adjusted to set the saturable-core reactor at the ideal operating point. Input signals, represented by the a.c. source symbol, are applied to the control input. The true power of the load circuit is controlled by the control input signal (a.c.)

The block diagram symbol for a magnetic amplifier is shown in figure 3-41. The triangle is the general symbol for an amplifier. The saturable-core reactor symbol in the center of the triangle identifies the amplifier as a magnetic amplifier. Notice the input and output signals shown. The input signal is a small-amplitude, low-power a.c. signal. The output signal is a pulsating d.c. with an amplitude that varies. This variation is controlled by the input signal and represents a power gain of 1000.
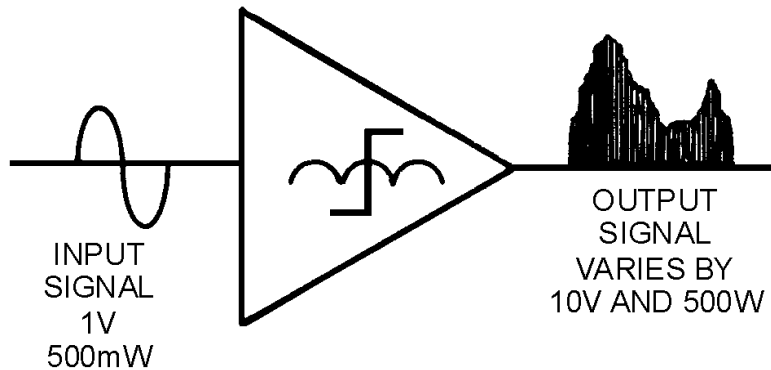
Figure 3-41.—Magnetic amplifier input and output signals.

Some magnetic amplifiers are designed so a.c. goes through the load rather than pulsating d.c. This is done by placing the load in a different circuit position with respect to the rectifier. The principle of the magnetic amplifier remains the same: Control current still controls load current.

Magnetic amplifiers provide a way of accurately controlling large amounts of power. They are used in servosystems (which are covered later in this training series), temperature or pressure indicators, and power supplies.

This chapter has presented only the basic operating theory of saturable-core reactors and magnetic amplifiers. For your convenience, simple schematic diagrams have been used to illustrate this material. When magnetic amplifiers and saturable-core reactors are used in actual equipment, the schematics may be more complex than those you have seen here. Also, you may find coils used in addition to those presented in this chapter. The technical manual for the equipment in question should contain the information you need to supplement what you have read in this chapter.

Q-46. At what portion of the magnetization curve should a magnetic amplifier be operated?

Q-47. How is the effect of load flux on control flux eliminated in a saturable-core reactor?

Q-48. What is the purpose of the rectifier in a magnetic amplifier?

Q-49. What is used to bias a magnetic amplifier so that the control winding remains free to accept control (input) signals?

Q-50. List two common usages of magnetic amplifiers.

SUMMARY

This chapter has presented information on differential amplifiers, operational amplifiers, and magnetic amplifiers. The information that follows summarizes the important points of this chapter.

A **DIFFERENCE AMPLIFIER** is any amplifier with an output signal dependent upon the difference between the input signals. A two-input, single-output difference amplifier can be made by combining the common-emitter and common-base configurations in a single transistor.
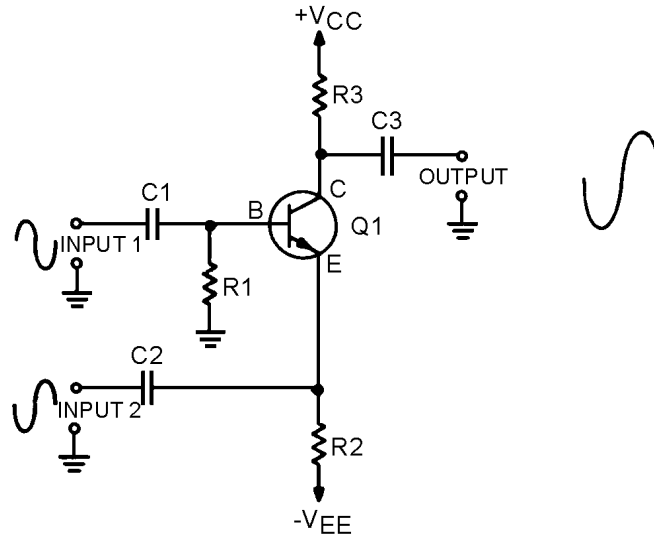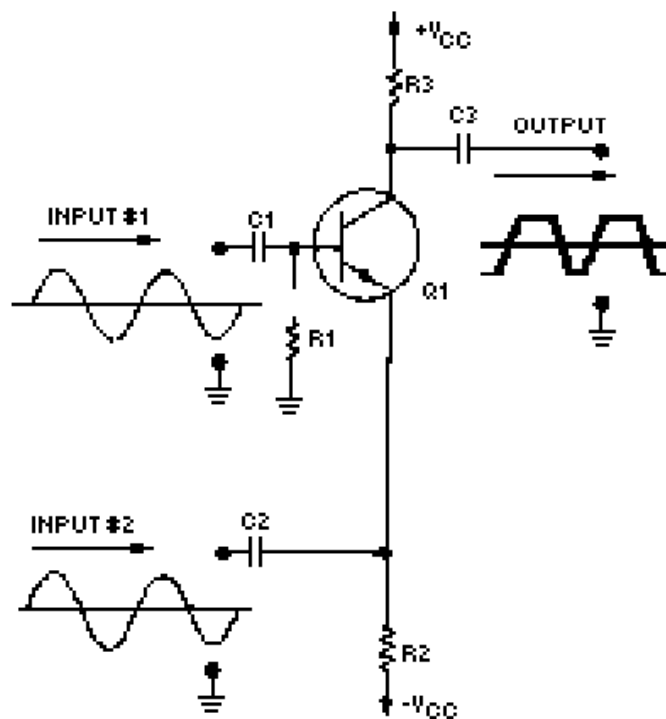
A difference amplifier can have input signals that are IN PHASE with each other, view (A), 180 DEGREES OUT OF PHASE with each other, view (B), or OUT OF PHASE BY SOMETHING OTHER THAN 180 DEGREES with each other, view (C).
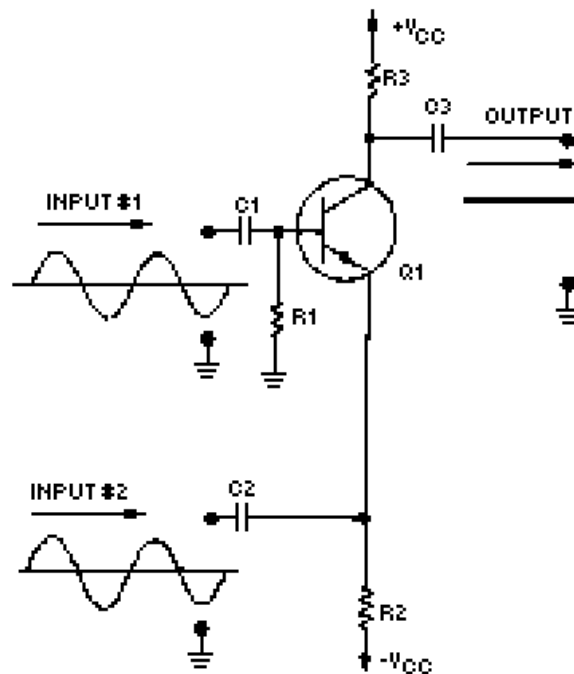
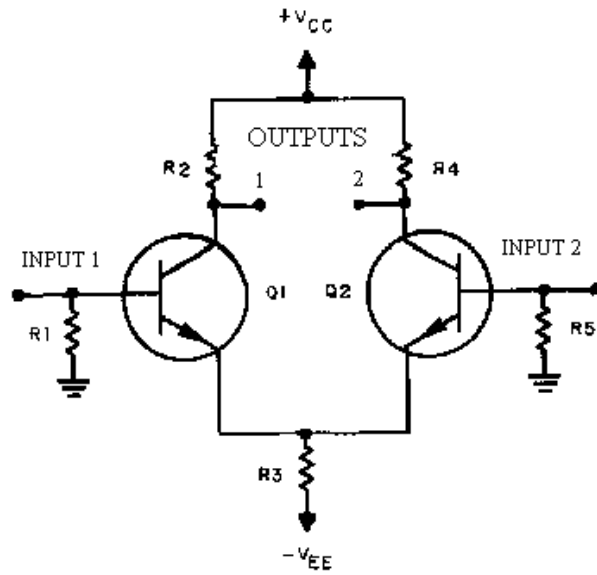

(A) DIFFERENTIAL AMPLIFIER IN PHASE
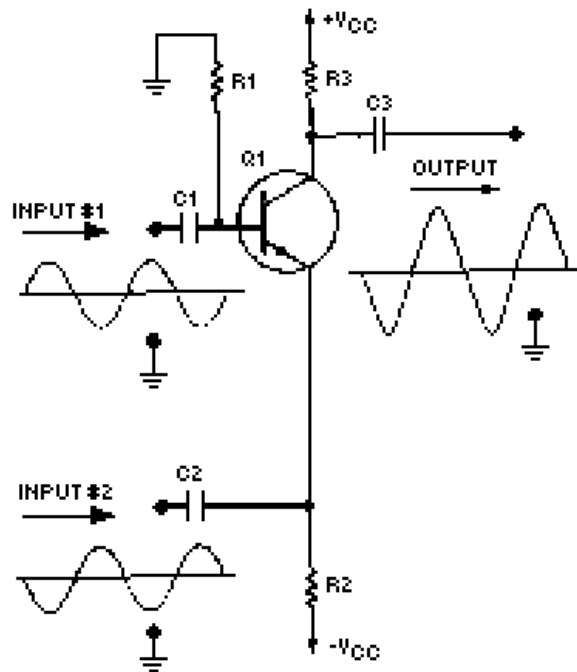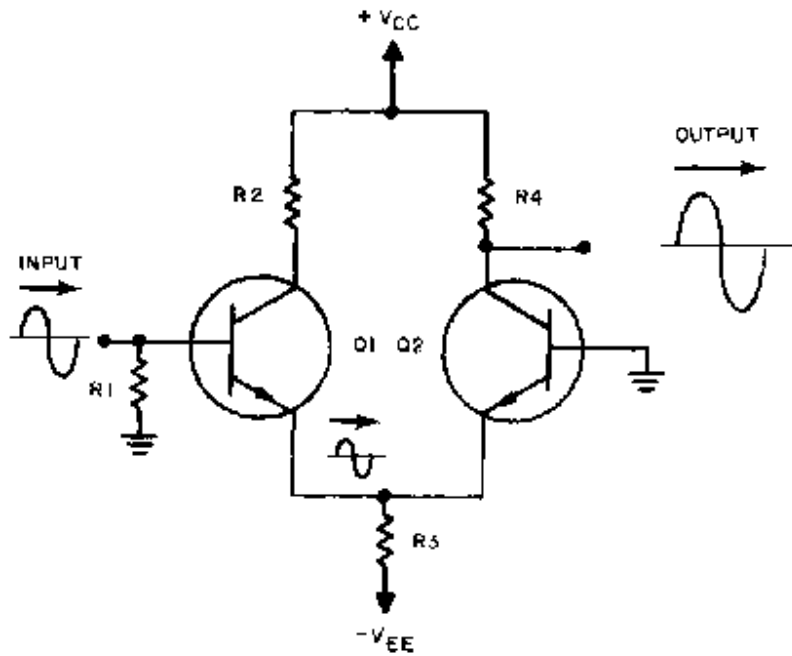
(B) DIFFERENTIAL AMPLIFIER 180° OUT OF PHASE

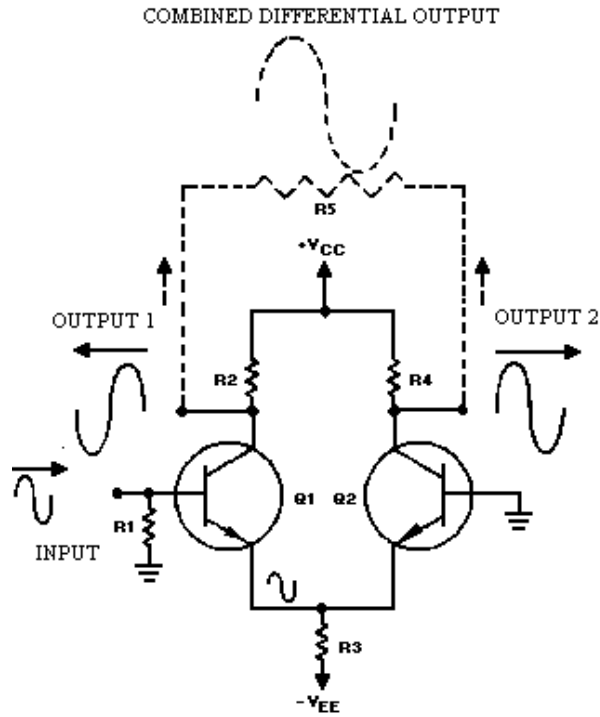(C) DIFFERENTIAL AMPLIFIER OUT OF PHASE OTHER THAN 180°

A **DIFFERENTIAL AMPLIFIER** has two possible inputs and two possible outputs. The combined output signal is dependent upon the difference between the input signals.

A differential amplifier can be configured with a SINGLE INPUT and a SINGLE OUTPUT

a SINGLE INPUT and a DIFFERENTIAL OUTPUT

COMBINED DIFFERENTIAL OUTPUT

OUTPUT 1

+V_{CC}

OUTPUT 2

R5

R2

R4

INPUT

R1

Q1 Q2

R3

-V_{EE}

or a DIFFERENTIAL INPUT and a DIFFERENTIAL OUTPUT.

COMBINED OUTPUT

OUTPUT 1

R6

+V_{CC}

OUTPUT 2

R2

R4

Q1 Q2

INPUT 1

R1

R5

INPUT 2

R3

-V_{EE}
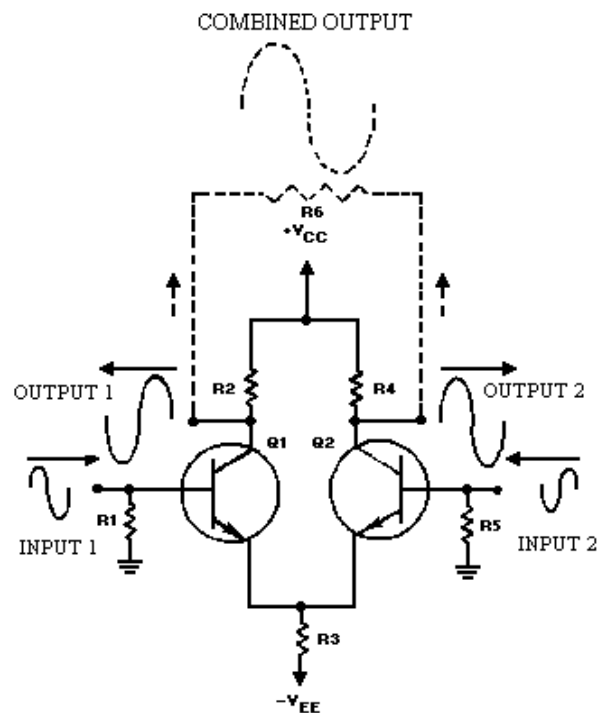
An **OPERATIONAL AMPLIFIER** is an amplifier which has very high gain, very high input impedance, and very low output impedance. An OP AMP is made from three stages: (1) a differential amplifier, (2) a high-gain voltage amplifier, and (3) an output amplifier.
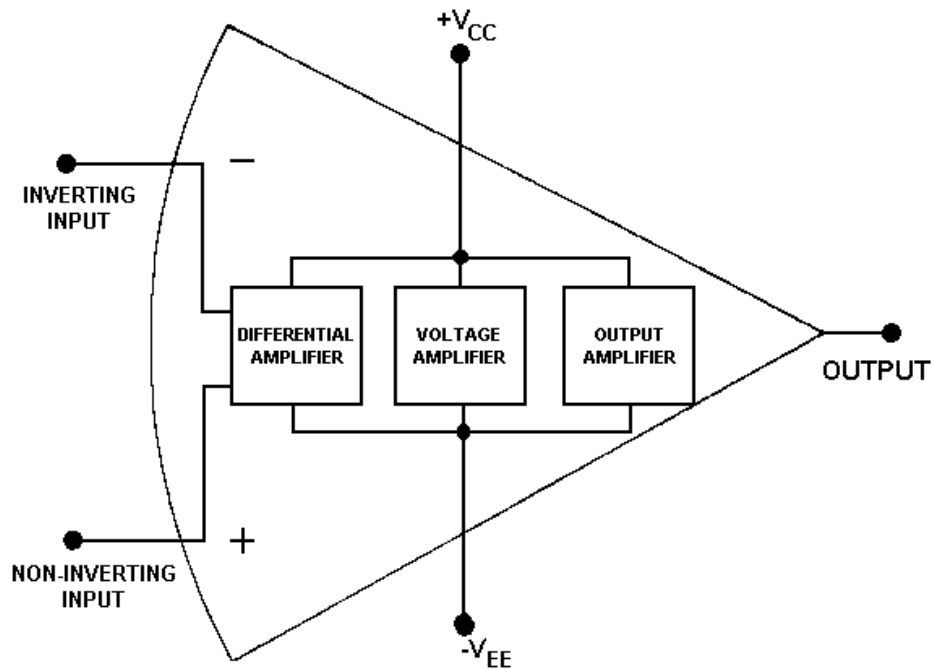
Operational amplifiers are usually used in a CLOSED-LOOP OPERATION. This means that degenerative feedback is used to lower the gain and increase the stability of the operational amplifier.

An operational amplifier circuit can be connected with an INVERTING CONFIGURATION
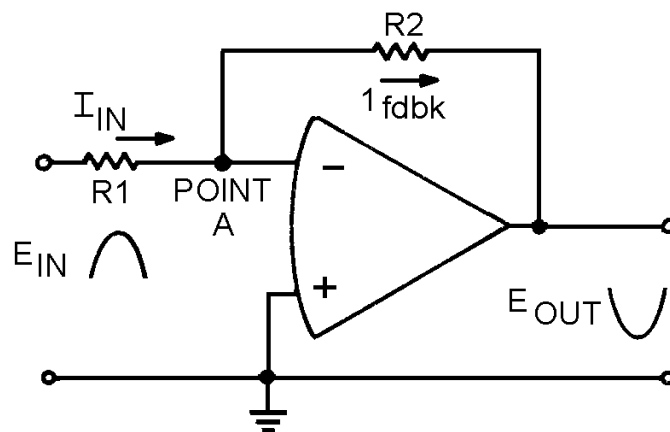

or a NONINVERTING CONFIGURATION.
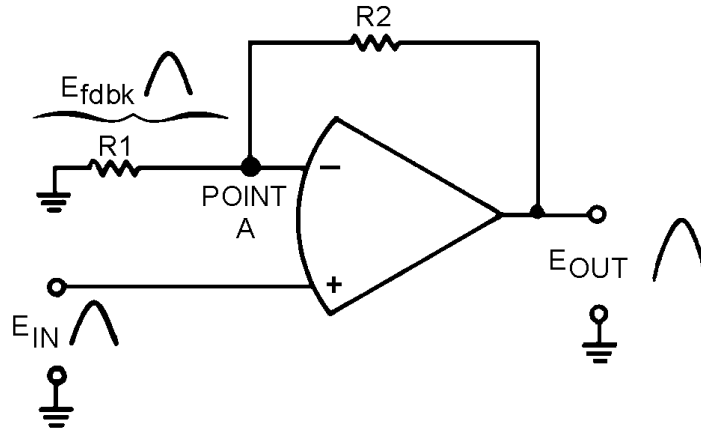
The **GAIN-BANDWIDTH PRODUCT** for an operational amplifier is computed by multiplying the gain by the bandwidth (in hertz). For any given operational amplifier, the gain-bandwidth product will remain the same regardless of the amount of feedback used.
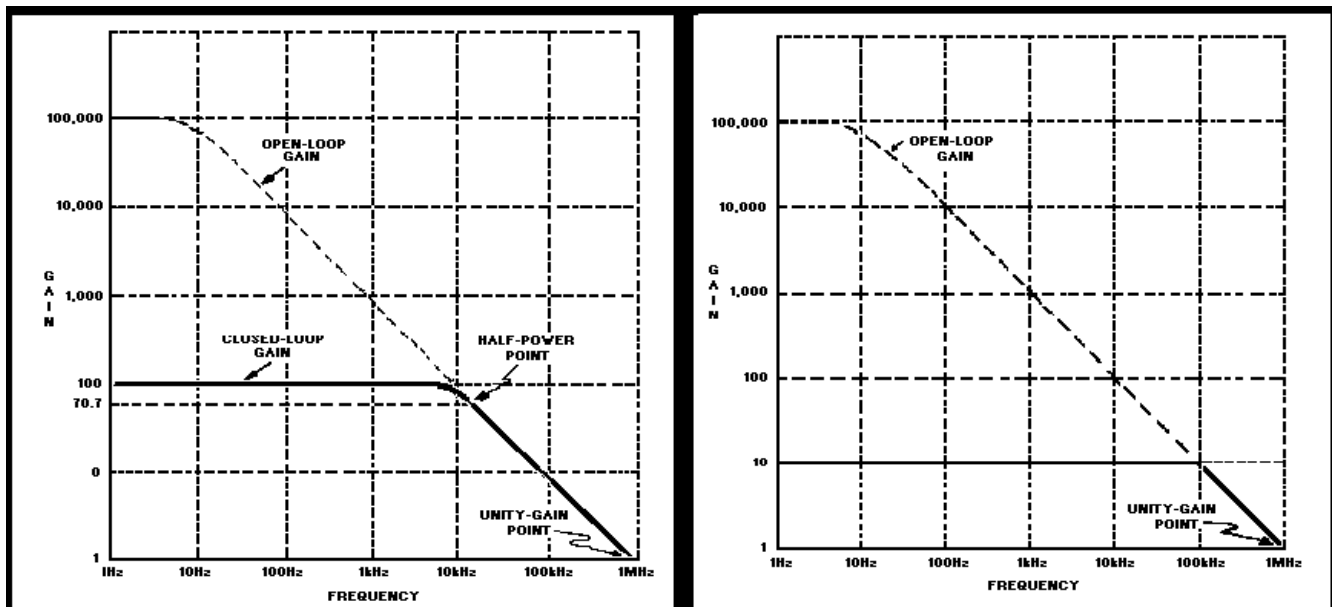
A **SUMMING AMPLIFIER** is an application of an operational amplifier in which the output signal is determined by the sum of the input signals multiplied by the gain of the amplifier:

$$E_{out} = gain\ (E1 + E2 \ldots)$$
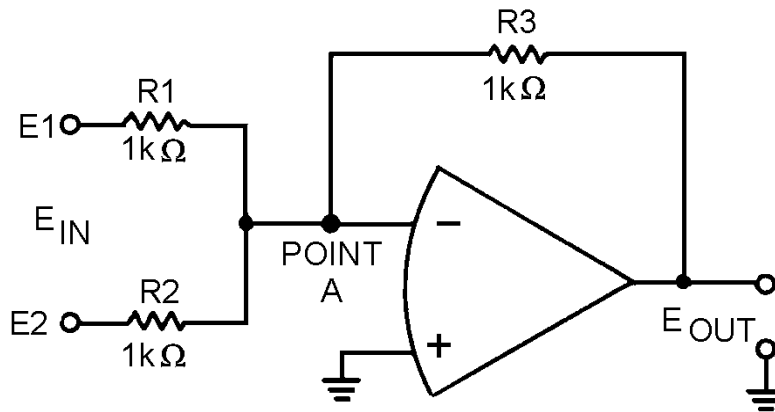
A **SCALING AMPLIFIER** is a special type of summing amplifier with the output signal determined by multiplying each input signal by a different factor (determined by the ratio of the input-signal resistor and feedback resistor) and then adding these products:

$$E_{out} = [(\frac{R_{fdbk}}{R_{in1}} \times E1) + (\frac{R_{fdbk}}{R_{in2}} \times E2) + (\frac{R_{fdbk}}{R_{in3}} \times E3)...]$$
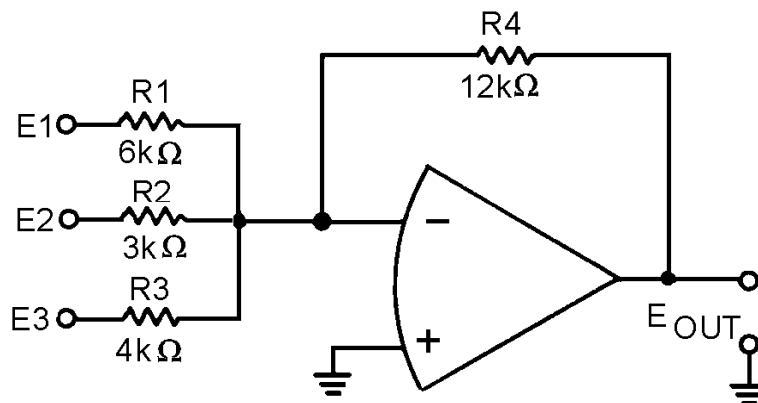

A **DIFFERENCE AMPLIFIER** is an application of an operational amplifier in which the output signal is determined by the difference between the input signals multiplied by the gain of the amplifier:

$$E_{out} = gain\ (E2 - E1)$$
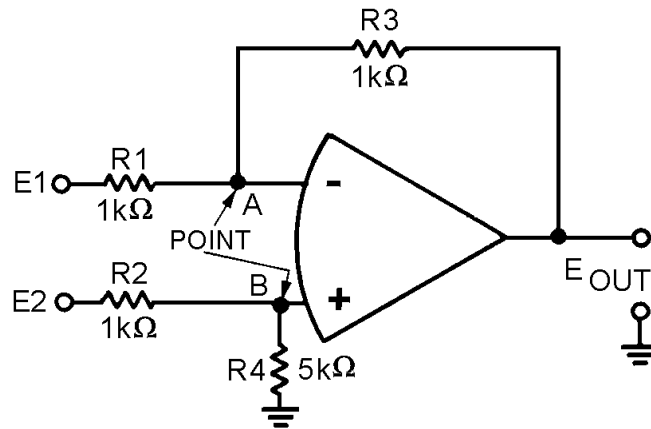
A **SATURABLE-CORE REACTOR** works upon the principle that increasing the current through a coil decreases the permeability of the core; the decreased permeability decreases the inductance of the coil which causes an increase in current (power) through the load.
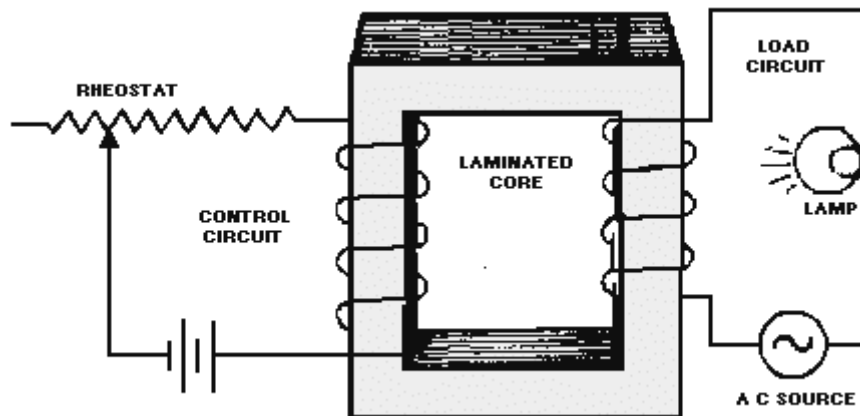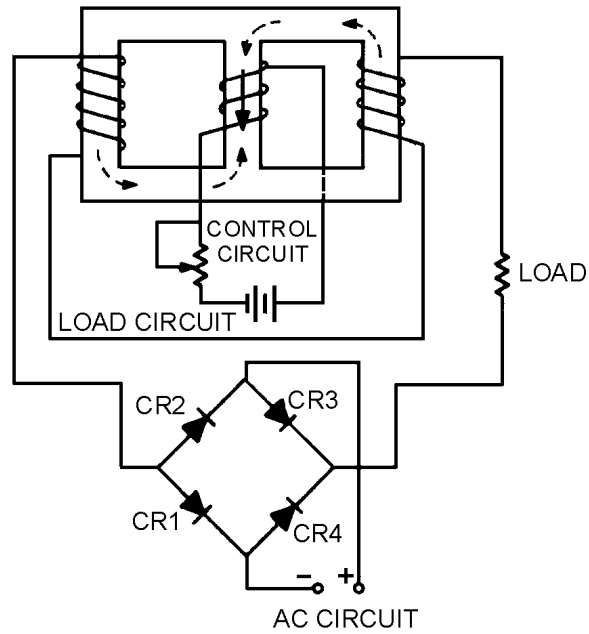

The **IDEAL OPERATING POINT** of a saturable-core reactor is on the KNEE OF THE MAGNETIZATION CURVE. At this point, small changes in control current will cause large changes in load current (power).
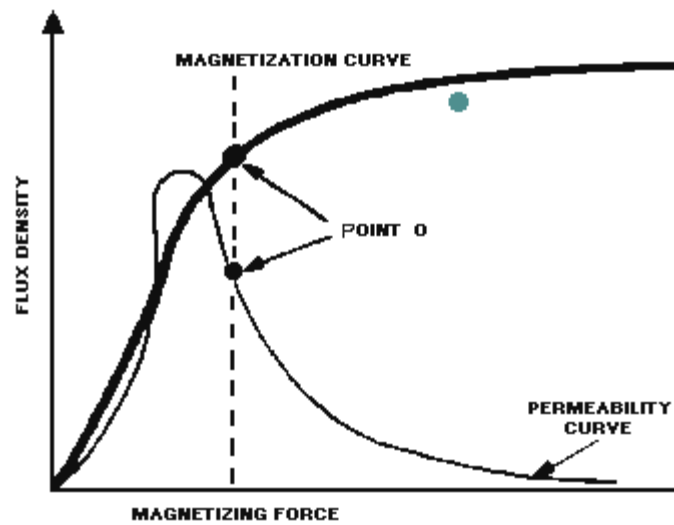
THREE-LEGGED and **TOROIDAL** saturable-core reactors solve the problem of load flux aiding and opposing control flux during alternate half cycles of the a.c. load current.
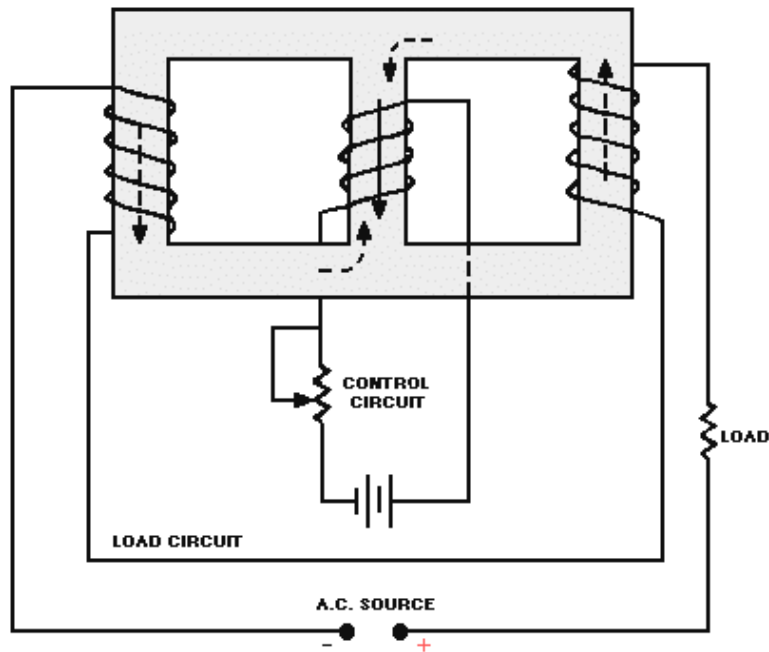
MAGNETIC AMPLIFIERS use the principle of electromagnetism to amplify signals. They are power amplifiers with a frequency response normally limited to 100 hertz or below. Magnetic amplifiers use a saturable-core reactor. A magnetic amplifier uses a RECTIFIER to solve the problem of HYSTERESIS LOSS in a saturable-core reactor.

A **BIAS WINDING** allows a d.c. bias voltage to be applied to the saturable-core reactor while a.c. control signals are applied to a separate control winding. In this way a magnetic amplifier can be set to the proper operating point.
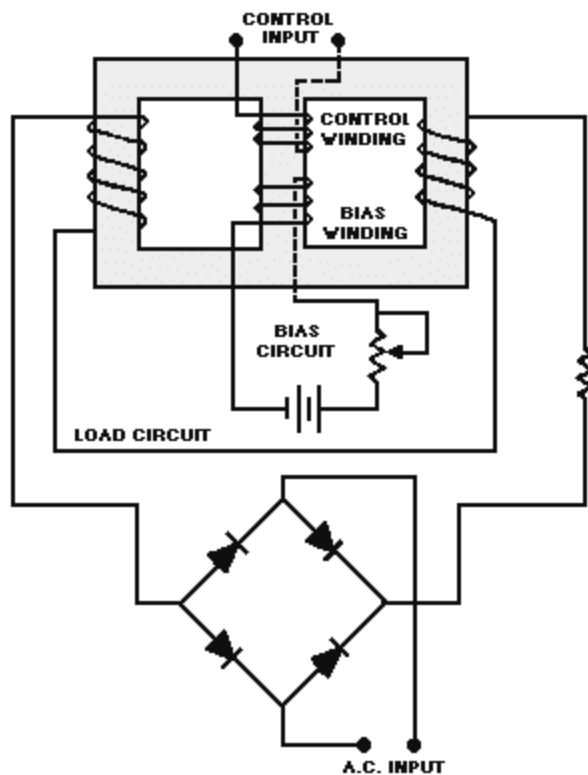
ANSWERS TO QUESTIONS Q1. THROUGH Q50.

A-1. *Two inputs, two outputs.*

A-2. *Common emitter (CE) and common base (CB).*

A-3. *No output (the signals will "cancel out").*

A-4. *Equal in shape and frequency to each input signal and larger in amplitude by two times than either input signal.*

A-5. *Equal in shape and frequency to the input signal; larger in amplitude than the input signal; half as large in amplitude as when two input signals were used that were 180 degrees out of phase.*

A-6. *A different shape than the input signals but larger in amplitude.*

A-7. *100 millivolts.*

A-8. *Each output will be a sine wave with a peak-to-peak amplitude of 100 millivolts. The output signals will be 180 degrees out of phase with each other.*

A-9. *200 millivolts.*

A-10. *0 volts (the input signals will "cancel out").*

A-11. *Each output signal will be 100 millivolts.*

A-12.

    a. *180 degrees out of phase with each other.*

    b. *Output signal number one will be in phase with input signal number two; output signal number two will be in phase with input signal number one.*

A-13. *200 millivolts.*

A-14.

    a. *100 millivolts.*

    b. *No.*

A-15. *Very high gain, very high input impedance, very low output impedance.*

A-16. *An integrated circuit (chip).*

A-17.
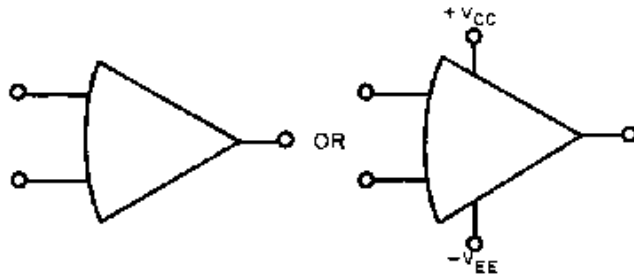
A-18.

      a.   Differential amplifier.

      b.   Voltage amplifier.

      c.   Output amplifier.

A-19.   The use of degenerative (negative) feed-back.

A-20.   Both the input signal and the feedback signal.

A-21.

      a.   Inverting.

      b.   Inverting.

A-22.   0 volts.

A-23.   Virtual.

A-24.   -50 millivolts.

A-25.   50 kilohertz (Gain = 10; Gain-Bandwidth Product = 500,000;

$$BW = \frac{500,000 \ (Hz)}{10} = 50kHz$$

A-26.   60 millivolts.

A-27.   1 megahertz.

Open-loop Gain-Bandwidth Product = Closed-loop Gain-Bandwidth Prod.

Open-loop Gain-Bandwidth Product = 200,000 × 30 (Hz)

Open-loop Gain Bandwidth Product = 600,000

Closed-loop Gain Bandwidth Product = 6 × Bandwidth

6,000,000 = 6 × Bandwidth

1,000,000 (Hz) = Bandwidth

A-28.   The adder simply adds the input signals together while the summing amplifier multiplies the sum of the input signals by the gain of circuit.

A-29.   Yes, a summing amplifier can have as many inputs as desired.

A-30.   A summing amplifier that applies a factor to each input signal beforeadding the results.

A-31.   A scaling amplifier.

A-32.

$$E_{out} = -72V$$

Solution:

$$E_{out} = -(+2V \times \frac{30k\Omega}{5k\Omega}) + (+6V \times \frac{30k\Omega}{3k\Omega})$$

$$E_{out} = -(+2V \times 6) + (+6V \times 10)$$

A-33.   0 volts. (The two inputs to the operational amplifier are both at 0 volts.)

A-34.   The difference amplifier multiplies the difference between the two inputs by the gain of the circuit while the subtractor merely subtracts one input signal from the other.

A-35.   No.

A-36.   A difference amplifier.

A-37.

$$E_{out} = +60V$$

Solution:

$$E_{out} = [(+11v) - (+5V)] \times \frac{R_3}{R_1}$$

$$E_{out} = (+6V) + \frac{20k\Omega}{2k\Omega}$$

$$E_{out} = (+6V) \times 10$$

A-38.   *0 volts. (The two inputs to the operational amplifier are both at the same potential.)*

A-39.   *An audio (or low) frequency power amplifier.*

A-40.   *A change in inductance in a series LR circuit causes a change in true power.*

A-41.   *It decreases.*

A-42.   *(a) Inductance increases; (b) true power decreases.*

A-43.   *Permeability decreases.*

A-44.   *A change in inductance.*

A-45.

A-46.   *The knee of the curve.*

A-47.   *Use two load windings whose flux effects cancel in the core of the reactor or use two load windings on two toroidal cores so that load flux always aids control flux in one core and opposes control flux in the other core.*

A-48.   *The rectifier eliminates hysteresis loss.*

A-49.   *A bias winding and associated circuitry.*

A-50.   Servosystems, temperature recorders, or power supplies.